U.S. Fish and Wildlife Service

Columbia-Pacific Northwest Region

# Leavenworth National Fish Hatchery
# Climate Change Vulnerability Assessment
## Final Report:  January 2022


**U.S. Fish and Wildlife Service**

**Columbia-Pacific Northwest Region**

**Climate Change Vulnerability Assessment Team**

**Please cite as:**

U.S. Fish and Wildlife Service (USFWS). 2022. Leavenworth National Fish Hatchery: Climate Change Vulnerability Assessment, Final Report, January 2022. Climate Change Vulnerability Assessment Team for National Fish Hatcheries, Columbia-Pacific Northwest Region, U.S. Fish and Wildlife Service, Portland, Oregon. 46 pages + 6 Appendices.

## ACKNOWLEDGEMENTS

This report was prepared by U.S. Fish and Wildlife Service (USFWS) staff: Bill Gale, Mid-Columbia Fish and Wildlife Conservation Office (FWCO), Leavenworth, Washington; Patty Crandell and Doug Peterson, Abernathy Fish Technology Center, Longview, Washington; Chris Pasley, Winthrop National Fish Hatchery (NFH), Winthrop, Washington; and Kyle Hanson, Andrew Goodwin and Don Campton, Regional Office, Portland, Oregon. Tim Mayer (Supervisory Hydrologist, Regional Office, retired) assisted with retrieving historical data for this report.

The following individuals from the USFWS's Hatchery Evaluation Team (HET) for Leavenworth National Fish Hatchery (NFH) assisted with the preparation of this report: Jim Craig (Leavenworth Complex Manager), Mathew Maxey (Hatchery Manager), Chris Griffith (Assistant Hatchery Manager), Christine Parker-Graham (Fish Health Veterinarian), Tim Bundy (Fish Health Biologist), Haley Muir (Fish Biologist), Matt Cooper (Fish Biologist), Travis Collier (former Assistant Hatchery Manager), Dave Irving (Leavenworth Hatchery Complex Manager, retired), and Adam Izbiki (Acting Hatchery Manager, Leavenworth NFH, retired).

## Table of Contents

# 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 USFWS's CCVA for Leavenworth 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 existing ability of a system or species to adjust to the impact of an environmental disturbance. ***Vulnerability*** of a system or species is an *impact* that cannot be adequately addressed by existing *adaptive capacity.*

## Background and methods

Leavenworth NFH is located near Leavenworth, Washington at river mile (RM) 2.8 of Icicle Creek, a tributary to the Wenatchee River 26 miles upstream from the Columbia River. The hatchery was originally authorized by the Grand Coulee Dam Project, as part of the Rivers and Harbors Act in 1935, and began operations in 1942.

Leavenworth NFH propagates an introduced hatchery population of Spring Chinook Salmon (*Oncorhynchus tshawytscha*) derived primarily from fish propagated at the Carson NFH.

---

[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.

Leavenworth NFH is also used currently for the acclimation and release of juvenile Coho Salmon (*O. nerka*), in cooperation with the Yakama Nation, to help restore extirpated populations in the Wenatchee River. Adult salmon returning to Leavenworth NFH must migrate upstream from the Pacific Ocean approximately 497 miles and must pass over seven Columbia River hydropower dams. The site elevation of the hatchery is approximately 1,140 feet above sea level.

Water management at Leavenworth NFH is complicated because of multiple water sources and variable irrigation withdrawals from Icicle Creek, the primary water source for the hatchery. Several shallow and deep wells provide pathogen-free ground water to the hatchery for egg incubation and supplemental water for holding adult broodstock and rearing of juvenile salmon. In addition, Leavenworth NFH supplements its surface water during the summer months (July – September) with controlled releases of cold water from upper Snow Lake (an alpine lake), the outflow of which feeds Snow Creek, a tributary to Icicle Creek approximately 1.0 river miles upstream of the water intake for the hatchery.

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 Leavenworth NFH to assess the *Sensitivity* of the hatchery and Spring Chinook Salmon to potential future changes in air temperature, precipitation, and surface and ground water temperature and availability. Climate projections for the 2040s were derived from downscaled temperature, precipitation, and hydrologic projections in the Icicle Creek 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 Leavenworth NFH to projected future climate.

We used the climate and hydrology projections, empirical data on recent fish culture conditions at Leavenworth 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 future 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 and supporting data to assess the *Impacts* of future climate to Chinook Salmon propagated at Leavenworth NFH and to the infrastructure of the hatchery.

---

[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/.

We then used expert opinions from the HET, NFH staff, and partners/comanagers to assess the *Adaptive Capacity* and *Vulnerability* of Leavenworth NFH to the future climate projected for the 2040s. Similar analyses were not performed for Coho Salmon because those fish are not directly propagated at Leavenworth NFH.

## Sensitivity of Leavenworth NFH: main points

- Leavenworth NFH is highly sensitive to low surface flows of Icicle Creek during the summer when juvenile Spring Chinook Salmon are on station and water needs of the hatchery and other users can exceed the total flow volumes available.
- Spring Chinook Salmon at Leavenworth NFH are moderately sensitive to increases in water temperatures during the summer months. This sensitivity is reduced considerably because of cool water discharges from upper Snow Lake.
- Spring Chinook Salmon at Leavenworth NFH have moderate to high sensitivity to disease risk, particularly Ich, as a function of rising surface water temperatures.
- Leavenworth NFH is considered to have moderate sensitivity to flood risks because the majority of the hatchery infrastructure – excluding the fish ladder and water intake structure – are above the flood plain of Icicle Creek. However, the hatchery may be particularly sensitive to rain-on-snow events like those that resulted in record flows of Icicle Creek in the fall of 1995 and 2006.
- The physical facilities and surface water sources for Leavenworth NFH are considered highly sensitive to wildfire risks.

## Exposure of Leavenworth NFH to future climate: main points

- Surface water temperatures of Icicle Creek are expected to be warmer in all months with mean annual water temperatures at RM 5.6, immediately upstream of the confluence of Snow Creek, projected to increase by 1.3 °C and increase by more than 2 °C during July, August, and September.
- Total annual and mean monthly precipitations in the 2040s for the Icicle Creek basin are projected to be largely unchanged from historic values but substantially more precipitation will fall as rain and less as snow with a projected 35% reduction in mean monthly snowpack.
- Mean *annual* flows projected for Icicle Creek in the 2040s will be similar or slightly higher than the modeled historical values, but the shape of the hydrograph for the 2040s was projected to be quite different from the historic average with higher flows in late fall and winter, lower peak runoff in June, and consistently lower flows in summer. Indeed, if water withdrawals upstream of the hatchery for irrigation continue at current rates, then Icicle Creek between the IPID diversion and the confluence of Snow Creek would most likely be dewatered during August and September.
- Water releases from Snow Lake in August and September are projected to be barely sufficient in the 2040s to meet the 42 cfs water right of the hatchery. However, a

proposed goal to maintain a minimum instream flow of 60 cfs adjacent to the hatchery may preclude withdrawal of any water by the hatchery during the summer if water continues to be diverted upstream of the hatchery at current rates for irrigation.
- The Icicle Creek basin will most likely transition from a historical snowmelt-driven watershed to a mixed snow-and-rain-driven watershed in the 2040s with substantial increases in peak flows in late fall and winter, particularly during rain-on-snow events.

## Impact of future climate to Leavenworth NFH: main points

- Higher water temperatures alone in the 2040s are not expected to preclude the ability of Leavenworth NFH to propagate Spring Chinook Salmon. However, faster growth rates due to higher water temperatures will result in greater total biomass of fish at the time of release with flow index values exceeding the fish health guideline of FI < 0.6 during the last eight months of the rearing cycle assuming that the current number of fish reared on station remains unchanged.
- Higher water temperatures projected for the 2040s during the summer months will likely increase disease risks, particularly for Ich.
- Significant reductions in the future availability of surface water during the summer months raise questions regarding the ability of Leavenworth NFH to maintain fish on station during August and September in the 2040s. After accounting for irrigation withdrawals upstream of the hatchery and the proposed goal to maintain a minimum instream flow of 60 cfs adjacent to the hatchery, virtually no surface water would be available for fish culture during August and September in the 2040s.
- Transition of the Icicle Creek watershed from primarily a snow-driven watershed historically to mixed rain-snow-driven watershed in the 2040s is expected to significantly increase flood risks in the late fall and winter and wildfire risks during the summer. However, we did not model or assess those risks directly but defer to USFWS hydraulic engineers and hatchery staff to assess the impacts associated with higher flood and wildfire risks in the 2040s.

## Adaptive capacity of Leavenworth NFH: main points

A Workgroup composed of the Assessment Team, the HET for Leavenworth NFH, and a representative of the U.S. Bureau of Reclamation identified the following adaptation strategies and options.

- Higher disease risks associated with warmer water temperatures in the 2040s will be controlled primarily through proactive preventive medicine with treatments implemented as needed at first detections of clinical disease. Potential future development of a partial reuse aquaculture system (PRAS) would be expected to further reduce disease risks through UV disinfection and the potential use of chillers. Enlargement and reconfiguration of the adult holding pond are desired to reduce fish densities and provide first-pass surface water rather than 3rd pass reuse water to adults prior to spawning or surplusing to the Tribes.

- Leavenworth NFH currently has very limited capacity to adapt to the lower summer flows of Icicle Creek projected for the 2040s. Under the existing hatchery infrastructure, little or no surface water is projected to be available for fish culture at Leavenworth NFH during August and September in the 2040s if current withdrawals by other users are maintained and the proposed goal of a minimum instream flow of 60 cfs for Icicle Creek is achieved. However, several infrastructure improvements have been proposed that would help conserve surface water availability during the summer (e.g., development of a full-scale PRAS, automation with remote control of the existing manual valve on the outlet of Upper Snow Lake, improved irrigation efficiencies and water conservation efforts, automation of other storage water resources, etc.).
- Leavenworth NFH appears to have little adaptive capacity at the present time to avoid high siltation and potential damage to the water intake structure, adult holding pond, and fish ladder during peak flows (> 15,000 cfs) projected for the 2040s. Those structures were damaged or severely impacted during the record peak flow (19,800 cfs) of Icicle Creek in November, 1995. However, a new water intake structure is scheduled for construction in 2023, and potential development of a full-scale PRAS would likely allow closure of the water intake during high siltation loads, thus protecting the hatchery infrastructure from siltation and reducing disease risks to juvenile fish on station.
- Hatchery staff consider Leavenworth NFH to be well buffered from the direct effects of future wildfires that will most likely increase in frequency in the 2040s and beyond. Most of the main buildings are covered with metal roofs, and fire protection measures are in place. The primary risk to the hatchery may be post-fire ash and sediment washing down from the upper Icicle Creek watershed and entering the water intake system of the hatchery following major wildfires.

## Vulnerability of Leavenworth NFH: main points

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

- The Spring Chinook Salmon Program at Leavenworth NFH is highly vulnerable to lower surface summer flows of Icicle Creek in the 2040s, primarily during August and September when projected water flows at the hatchery intake may be insufficient to meet the 42 cfs water right of the hatchery. Indeed, the projected shortage of water in August and September will most likely preclude the ability of Leavenworth NFH to maintain juvenile Chinook Salmon on station year round without major infrastructure adaptations (e.g., development of a full-scale PRAS), particularly if instream flows of Icicle Creek adjacent to the hatchery are maintained at proposed levels (minimum 60 cfs).
- Disease risks and vulnerabilities of juvenile and adult Spring Chinook Salmon are expected to increase with increasing water temperatures in the 2040s. Ich and BKD are

the diseases of greatest concern. The adaptive measures available currently to mitigate those risks are primarily preventive medicine and proactive fish health monitoring.

- Leavenworth NFH appears to be only moderately vulnerable to future floods and higher peak flows of Icicle Creek projected for the 2040s because the majority of the hatchery infrastructure (buildings, raceways) is above the flood plain. However, the water intake structure and fish ladder have been significantly impacted in the past from very high peak flows, and those vulnerabilities continue. The water intake structure on Icicle Creek is scheduled to be replaced in 2023 with a new design that considered the highest peak flow recorded in Icicle Creek (19,800 cfs), and completion of that project is expected to reduce flood vulnerabilities considerably.
- Although wildfire risks are expected to increase in the future because of warmer-drier summers, the vulnerability of Leavenworth NFH to the direct effects of wildfire are considered comparatively low because of proactive management by hatchery staff to buffer the hatchery from those risks. The greatest vulnerability of Leavenworth NFH to future wildfires may be the indirect impacts of ash and suspended sediments that are washed down the watershed during high water events and enter the water intake structure of the hatchery, thus posing an additional health risk to fish on station.

## 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 and Wenatchee rivers, from the Pacific Ocean to Icicle Creek, 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 (*Oncorhynchus* spp.) through the 21st Century.

## Conclusions

1. Higher water temperatures alone will not preclude the ability of Leavenworth NFH to propagate Spring Chinook Salmon in the 2040s. However, disease risks are expected to increase, particularly for Ich and BKD, because of higher water temperatures and faster fish growth rates with a consequential increase in flow and density index values. Those latter index values are projected to approach or exceed the upper limit of fish health guidelines, assuming no changes in infrastructure or in the number of fish reared.

2. Significant decreases in surface water flows of Icicle Creek during the summer months may preclude the ability of Leavenworth NFH to maintain fish on station during August and September in the 2040s. Virtually no surface water would be available for fish culture in August and September if withdrawals by other users continue at current rates and the proposed minimum instream flow goal of 60 cfs is achieved. Alternatively, Icicle

Creek would most likely be dewatered, or nearly so, between the hatchery intake and the hatchery outflow if the hatchery exercised its full 42 cfs water right.

3. The Icicle Creek watershed will transition from primarily a snowmelt-driven watershed historically to a mixed rain-and-snowmelt-driven watershed by the 2040s. This transition will significantly increase peak flows of Icicle Creek in the late fall and winter with a commensurate increase in flood risks. Those hydrology projections for the 2040s suggest a higher likelihood of major impacts to the hatchery infrastructure because of increases in the magnitude and/or frequency of extreme high water events.
4. Higher mean air temperatures, reduced snow pack, and lower surface water flows throughout the Icicle Creek watershed in summer will further increase wildfire risks in the 2040s. A major indirect impact of wildfire is reduced water quality from ash and silt that can impact fish health following major storm events.

## Recommendations

1. Continue testing a prototype partial reuse aquaculture system (PRAS) at Leavenworth NFH. If considered feasible, design a full-scale PRAS capable of supporting the current Spring Chinook Salmon program during the summer and early fall when the quantity of surface water available from Icicle and Snow Creeks may be insufficient for maintaining Chinook Salmon on station.
2. Install infrastructure to automate the current manual valve on the outlet pipe for upper Snow Lake to allow real-time remote operation of the valve.
3. Continue to support automation of the control valves on the outlets of the four IPID reservoirs in the upper Icicle Creek watershed.
4. Develop a contingency plan for transferring all or a portion of Spring Chinook Salmon juveniles from Leavenworth NFH to another hatchery or location during the summer months in the event that the quantity of surface water available for fish culture is not sufficient for maintaining an entire brood year of fish. A similar contingency plan may exist currently at Warm Springs NFH. Future development of a full-scale PRAS at Leavenworth NFH and/or implementation of recommendations #2 and #3 may obviate the need for developing the contingency plan recommended here.
5. Reconfigure and enlarge the adult collection and holding ponds to reduce fish densities and the risk of disease to adult Chinook Salmon held on station prior to spawning and/or surplusing to the Tribes.
6. As part of recommendation #5 or during construction of the new Icicle Creek water intake structure scheduled in 2023, construct a direct water supply line from the new water intake pipe/structure to the adult holding ponds to provide fresh, first-pass water to adult Chinook Salmon held for broodstock. This measure will increase water quality and reduce disease risks.

7. Continue to maintain groundwater infrastructure and well-rehabilitation activities.
8. Investigate additional groundwater options and infrastructure upgrades to increase the quantity of groundwater available during the summer.
9. Continue working through the Icicle Work Group to develop a Decision Support Tool for water management of Icicle Creek.
10. Solicit a hydrologist and/or engineer to assess future flood risks and potential damage to the hatchery infrastructure during a future 100-year peak flow of Icicle Creek that could approach or exceed 20,000 cfs in the 2040s. Based on that hydrology assessment, implement measures deemed necessary to protect highly vulnerable areas of the hatchery infrastructure (e.g., fish ladder, settling pond) in the event of a major episodic flood event.
11. Update the Station Safety Plan and ensure all possible measures to reduce wildfire risks are in place.

# 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 to climate change and (b) developing adaptation and mitigation strategies to cope with those expected 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 modelled climates (USFWS 2010a, b). The Fish and Aquatic Conservation Programs 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 initial pilot assessment (USFWS 2013a) followed by assessments at Quilcene NFH (USFWS 2016), Makah NFH (USFWS 2019), Warm Springs NFH (USFWS 2021a), and Entiat NFH (USFWS 2021b).[6]

The report presented here describes the results of the USFWS's *quantitative* CCVA for Leavenworth NFH and the one species propagated there: Spring Chinook Salmon (*Oncorhynchus tshawytscha*).[7] Leavenworth NFH is located at river mile (RM) 2.8 on Icicle Creek, a tributary to the Wenatchee River in Leavenworth, Washington on the east side of the Cascade Mountains in the Columbia River Basin (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

---

[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).

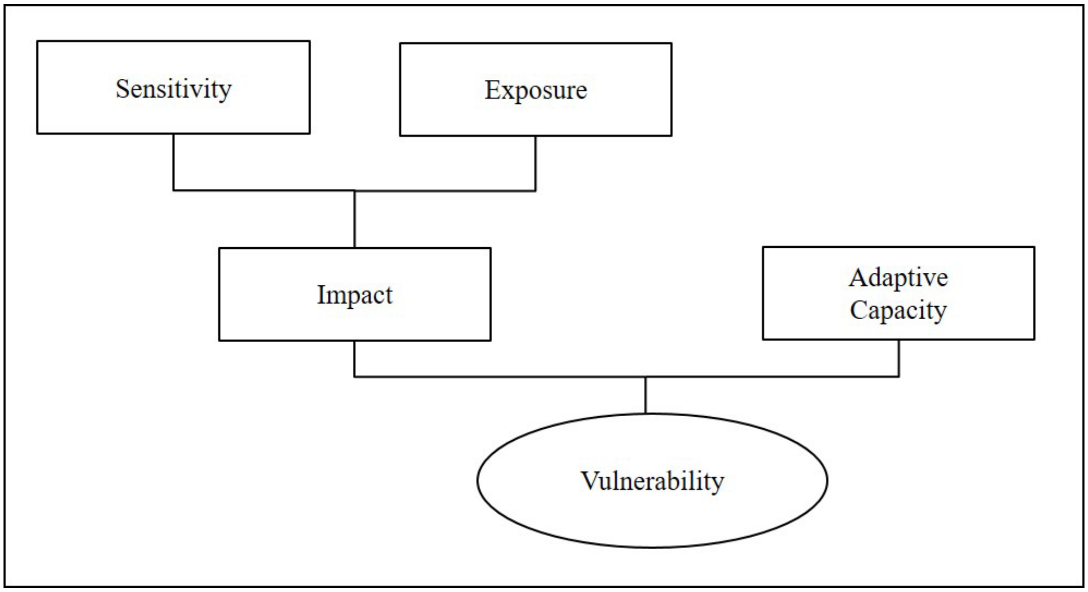


**Figure 1.** Key components of a vulnerability assessment.

***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 Leavenworth NFH and (b) the current biomass capacity and productivity limitations of rearing Spring Chinook Salmon to the smolt stage of development at Leavenworth 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 Icicle Creek basin and the Leavenworth 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 Spring Chinook Salmon program at Leavenworth 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 Spring Chinook Salmon program at Leavenworth 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 time 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 the 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 hatchery 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 impacts that will likely 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.

# IV. BACKGROUND

## A. **Icicle Creek watershed**

Leavenworth NFH is located at RM 2.8 on Icicle Creek, a tributary to the Wenatchee River 26 miles upstream from the Columbia River, immediately south of Leavenworth, Washington (Figure 2). The Wenatchee River flows southeasterly from the east slopes of the Cascade Mountains and enters the Columbia River at RM 468 in Wenatchee, Washington. The Wenatchee River watershed encompasses approximately 1,371 square miles with many tributaries draining subalpine regions of the Alpine Lakes and Glacier Peak Wilderness Areas. Adult fish returning to Leavenworth NFH must migrate 497 miles upstream and past seven Columbia River hydropower dams. The site elevation of the hatchery is approximately 1,140 feet above sea level.

Icicle Creek provides limited spawning and rearing habitat for anadromous salmonid fishes. A high-gradient boulder field and cascades at RM 5.6, compounded by very low water flows during the summer, impedes upstream migration of salmonid fishes and is believed to be a complete barrier to Chinook Salmon. A natural barrier falls exists at RM 24 of Icicle Creek, thus yielding approximately 18 miles of potential anadromous fish habitat upstream of the boulder field.

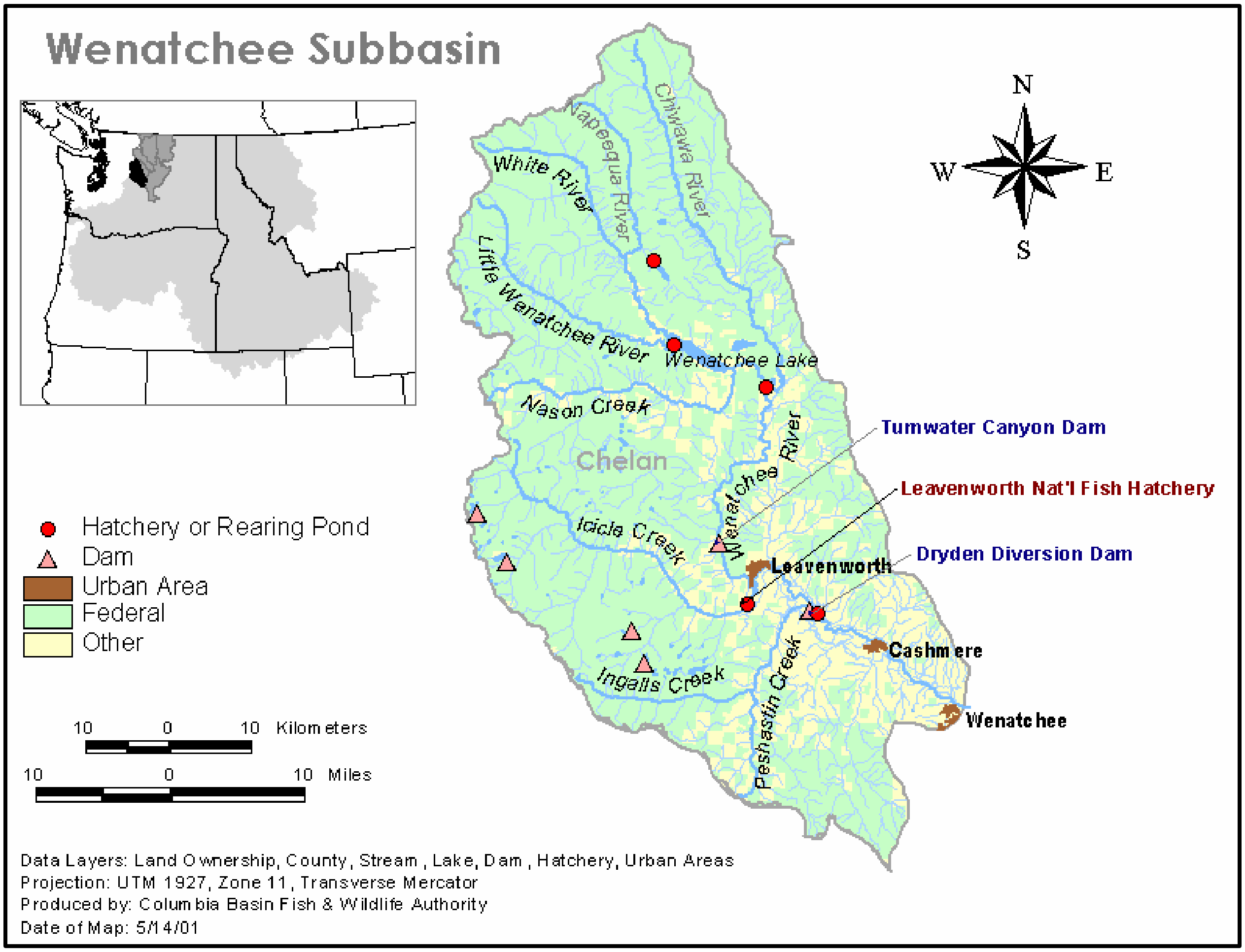


**Figure 2.** Location of the Icicle Creek watershed within the Wenatchee River basin. Leavenworth National Fish Hatchery is located at river mile (RM) 2.8 of Icicle Creek, immediately south of Leavenworth, Washington. The Wenatchee River enters the Columbia River at RM 468 in Wenatchee, Washington.

## B. **Leavenworth NFH infrastructure**

Leavenworth NFH was originally authorized in 1937 by the Grand Coulee Fish Maintenance Project as part of the Rivers and Harbors Act (49 Statue 1028) and reauthorized in 1938 by the Mitchell Act (52 Statue 345). The hatchery was constructed 1939 – 1942 and began operations in 1942. The hatchery includes the following: (a) a nursery/office building with 72 egg-incubation troughs, 540 egg incubation trays in 36 stacks, and 122 nursery tanks; (b) a maintenance shop, a feed/cold storage building, four equipment storage buildings, and three water-reuse pump buildings; (c) seven wells, two 15x150’ adult-holding ponds, 45-8x80’ concrete raceways in three banks of 15 raceways per bank (water flows in series from the upper bank to the middle bank to the lower bank), 14-10x100’ covered raceways, 40 small and 22 large Foster-Lucas rearing ponds; and (d) four residence buildings for staff (Cooper et al. 2006; Potter et al. 2018).

## C. **Water resources at Leavenworth NFH**

Water management at Leavenworth NFH uses a complex combination of surface and groundwater to rear salmon. Water sources at the hatchery include Icicle Creek, supplemental summer releases from Snow and Nada Lakes in the Alpine Lakes Wilderness Area (Icicle Creek watershed), and seven wells. Actual temperatures of the water supplied to fish at the hatchery often reflects mixed temperatures from two or more sources (e.g., Icicle Creek, Snow Creek, ground water). Well water is used to cool or warm stream water during critical periods of the fish rearing cycle. An extensive system is in place to monitor water flows and temperatures of the various sources year round (Table B3, Figures B2 and B3, Appendix B). These various water sources – including their respective mean monthly temperatures and their relative contributions as a mixed water source for rearing salmon at Leavenworth NFH – were all modeled for assessing the exposure and impacts of projected future climates at the hatchery in the 2040s (Appendix B, pages 5–10).

### *Icicle Creek*

Surface water is diverted from Icicle Creek to the hatchery at RM 4.5, approximately 0.6 miles upstream from the hatchery property. The current Icicle Creek water intake and some of the water delivery system is part of the original construction of the hatchery that occurred 1939 – 1942. A bypass channel adjacent to the hatchery – referred to as the *hatchery channel* – is occasionally re-watered to recharge shallow wells via percolation to supplement the hatchery water supply as needed (Figure B2). The Icicle-Peshastin Irrigation District (IPID) withdraws water from Icicle Creek at RM 5.8 immediately upstream of the boulder field with a water right of 117 cubic feet per second (cfs). An additional 3 cfs water right is provided to the City of Leavenworth for domestic use (Figure B3). The IPID diversion reduces substantially the amount of Icicle Creek water available to the hatchery during the spring and summer (April – September, Table B4).

### *Snow and Nada lakes*

Leavenworth NFH has water rights of 16,000 acre-feet per year from Upper Snow Lake, an alpine lake with a capacity of approximately 12,450 acre-feet. The lake is approximately seven miles from Icicle Creek and 5,000 feet higher in elevation (Figure 3). A one-half-mile-long bored tunnel with valve, installed in the bottom of the lake by the U.S. Bureau of Reclamation in 1939, allows water to be diverted into Nada Lake at a controlled rate of approximately 45 – 60 cfs during the low flow summer months (July – September) or as soon as the temperature of Icicle Creek reaches 14.5 ºC and needs to be cooled for fish culture at the hatchery. Water from Nada Lake flows into Snow Creek and then Icicle Creek at RM 5.5, approximately one mile upstream of the water intake for the hatchery and 0.3 miles downstream of the IPID diversion (Table B3). The supplemental water from Snow Lake ensures the water-right availability to the hatchery of 42 cfs of surface water from Icicle Creek (Table 1). During those low summer-flow situations, water originating from Upper Snow Lake ultimately represents the majority of the surface water that reaches the hatchery (Fraser 2015; Potter et al. 2017).

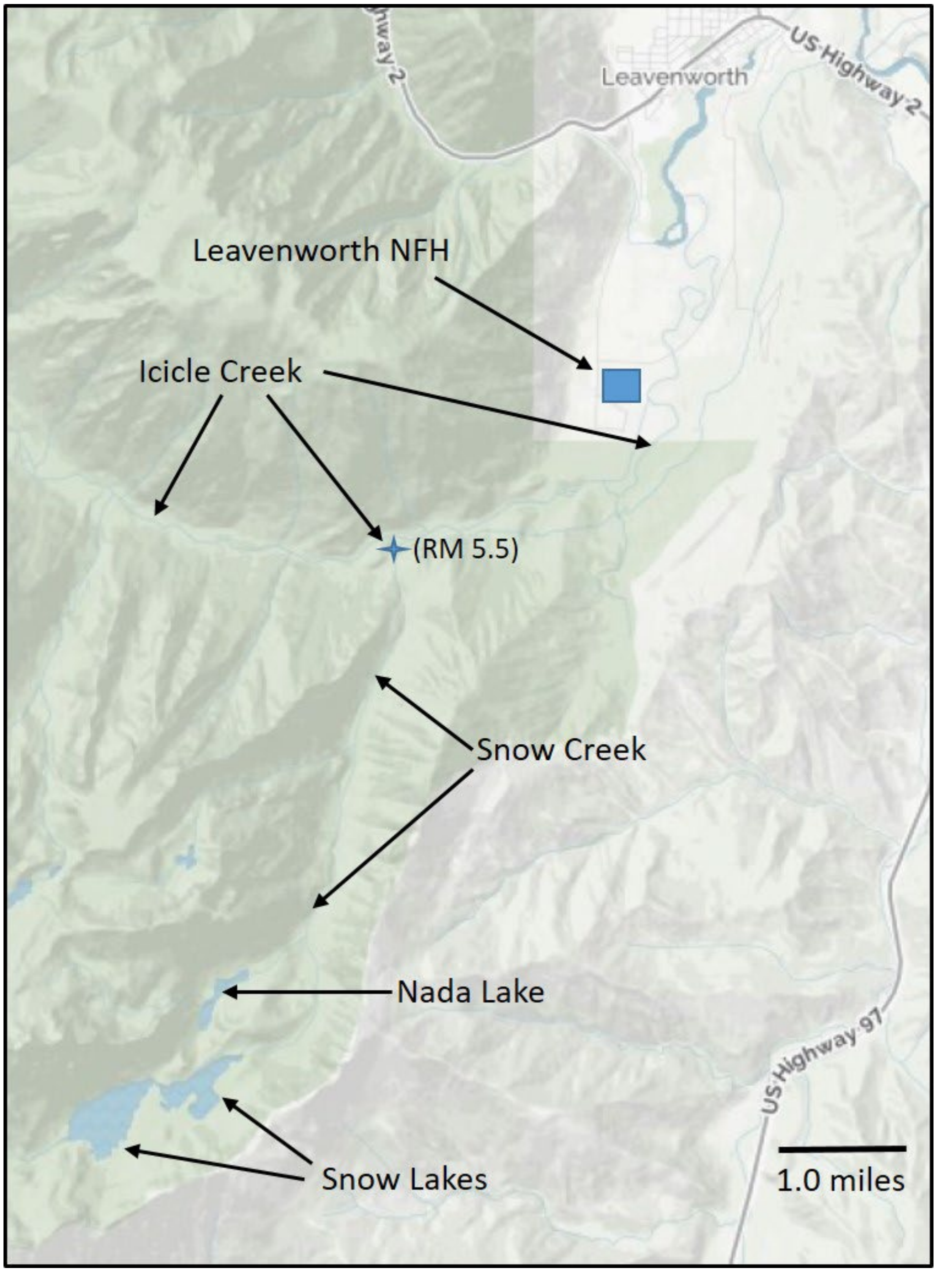


**Figure 3.** Location of Snow and Nada lakes within the Icicle Creek watershed. Water is diverted from Upper Snow Lake (lower-left) through a bored tunnel to Nada Lake from which water outflows into Snow Creek. Water diversions from Upper Snow Lake (45 – 60 cfs) are used to supplement Icicle Creek at RM 5.5 during the summer to maintain an adequate water supply and temperature for Leavenworth National Fish Hatchery. The Icicle-Peshastin Irrigation District (IPID) has a primacy water right of 117 cfs at the IPID's diversion at RM 5.8 of Icicle Creek.

### *Ground water*

Groundwater is drawn from "shallow wells" (Wells No. 1, 2, 3, and 7) and "deep wells" (Wells No. 4, 5, and 6) for fish culture at specific times during the rearing cycle (Figure B2).

### *Reuse water*[9]

The middle and lower banks of the three-level 8' x 80' raceways have the capability to be supplied with gravity-feed reuse water in series from the upper bank. However, for the current Spring Chinook Salmon program, all three raceways currently receive single-pass surface water. The upper bank can also receive fresh well water, but the middle and lower banks can only receive well water via serial reuse from the upper bank.

### *Water rights*

Water quantity and high summer temperatures in Icicle Creek are significant factors affecting instream flows, hatchery operations and capabilities. Major water right holders for Icicle Creek are the Icicle/Peshastin Irrigation District (117 cfs at RM 5.8), City of Leavenworth (3 cfs at RM 5.8), Leavenworth NFH (42 cfs at RM 4.5), and the Cascade Orchard Irrigation Company (12 cfs at RM 4.5).[10] Water right sources for Leavenworth NFH are summarized in Table 1.

**Table 1.** Water rights appurtenant to the Leavenworth NFH and temperature range of sources. Certificate G4-27115C allows for a total water withdrawal of 3,900 gpm for Wells 4 through 7 combined (*). Upper water temperatures for Icicle and Snow Creeks measured at IC1 and IC2, respectively (see Figure B3).

| Source | Certificate Number | Purpose or Use | Priority Date | Amount | Temperature Range |
|---|---|---|---|---|---|
| Icicle Creek | 1824 | Fish culture | 1942 | 42 cfs | 0 – 18.5 °C |
| Snow and Nada lakes | 1825 | Fish culture | 1942 | 16,000 acre-ft./yr. | |
| Snow Creek[11] | 1825 | Fish culture | 1942? | (45 – 60 cfs) | 0 – 16.7 °C |
| Groundwater Well No. 3 | 016378 | Fish culture | 1939 | 700 gpm | 6.7 – 9.9 °C |
| Groundwater Well No. 2 | 016379 | Fish culture | 1940 | 900 gpm | 8.3 – 9.7 °C |
| Groundwater Well No. 1 | 3103-A | Fish culture | 1957 | 1,200 gpm | 5.7 – 12.2 °C |
| Groundwater Well No. 4 | G4-27115C | Fish culture | 1980 | 800 gpm* | 6.2 – 9.1 °C |

[9] Summary of current use provided by Mathew Maxey, Manager, Leavenworth NFH, personal communication, December 22, 2021.

[10] The USFWS is responsible for providing up to 12 cfs of water to the Cascade Orchard Irrigation Company (Article 14, contract between the U.S. and the Cascade Orchard Irrigation Company, dated November15, 1939).

[11] Part of the Snow and Nada lakes water right. A maximum of 42 cfs of water can be withdrawn via conveyance to Icicle Creek and Certificate Number 1824.

| Source | Certificate Number | Purpose or Use | Priority Date | Amount | Temperature Range |
|---|---|---|---|---|---|
| Groundwater Well No. 5 | G4-27115C | Fish culture | 1980 | 1,500 gpm* | < 11.0 °C |
| Groundwater Well No. 6 | G4-27115C | Fish culture | 1980 | 1,200 gpm* | 10.3 – 11.4 °C |
| Groundwater Well No. 7 | G4-27115C | Fish culture | 1980 | 400 gpm* | 6.3 – 8.2 °C |

## D. **Spring Chinook Salmon program**

Leavenworth NFH has reared and released Chinook Salmon annually since 1942, except for brood years 1967 and 1968. The hatchery currently propagates an introduced hatchery stock of Spring Chinook Salmon for harvest in tribal and recreational fisheries.[12] Spring Chinook Salmon are reared in freshwater for approximately 20 months prior to release as age 1+ fish (yearlings) in the spring of their second year. The primary fishery on adult Spring Chinook Salmon returning to the hatchery occurs in the lower reach of Icicle Creek downstream from the hatchery. Additional fish are caught in the Wenatchee and Columbia rivers. The current interim release goal while improvements are ongoing at the hatchery is 1.2 million smolts with a broodstock collection goal of 1,000 adults (500 pairs). The release goal will be increased to the U.S. v. Oregon agreement of 1.625 million smolts when improvements are completed. The broodstock goal will remain at 1,000 adults.

Adult Chinook Salmon returning to the hatchery are typically captured for broodstock from mid-May to early July and retained in holding ponds through early September. Formalin (167 ppm for 1 hour) is administered prophylactically into the holding ponds, three times per week, to inhibit fungus and parasites. Spawning typically occurs from mid-August until early September with a targeted 1:1 female to male ratio.

Random samples of adult broodstock are tested for viruses and specific pathogens at the time of spawning. The focus is on the detection of BKD, Infectious Pancreatic Necrosis Virus (IPNV), and Infectious Hematopoietic Necrosis Virus (IHNV). Sampling protocols include testing all female broodstock for their infection levels of *R. salmoninarum* and the clinical presence of BKD based on an Enzyme-Linked Immunosorbent Assay (ELISA) and visual observations of kidney tissues. Fertilized eggs from females with high infectious levels of *R. salmoninarum* are culled.

[12] Between 1974 and 1985, Leavenworth NFH imported Spring Chinook Salmon eggs from other Columbia River hatcheries, primarily Carson NFH, but also Cowlitz River State Hatchery (Washington) and Little White Salmon NFH. Fish and/or eggs have not been imported to Leavenworth NFH since 1985, and the broodstock has consisted entirely of adult fish that have returned (volunteered) to the hatchery. Based on broodstock records and genetic studies, the current hatchery stock is more closely related to the Carson NFH stock than the natural population in the Wenatchee River with an ancestry derived primarily from Carson NFH. This latter stock was developed at Carson NFH (Wind River, Washington) in the late 1950's and early 1960's from adult Spring Chinook Salmon trapped at Bonneville Dam.

Fertilized eggs are water hardened in disinfectant and incubated separately by female parent until ELISA results are available (generally within one month). Eggs hatch by mid-December, and the resulting fry are initially transferred to indoor nursery tanks in the main hatchery building prior to ponding to outside raceways in the spring. Fry in the indoor nursery tanks are maintained on 100% well water as long as possible, but surface water is added during the last few weeks as fish grow to maintain flow index values within fish health guidelines (see below). A portion of yearling Chinook Salmon may be moved from raceways to adult holding ponds in October to accommodate the holding of Coho Salmon broodstock for the Yakama Nation.

USFWS fish health guidelines for Spring Chinook Salmon at Leavenworth NFH dictate density index values (lbs./in.*$ft^3$) less than 0.2, flow index values (lbs./in.* gpm) less than 0.6, and water exchange rates in raceways less than 30 minutes to minimize stress and disease risks. Throughout the rearing cycle, USFWS Fish Health staff conduct monthly health examinations to monitor and assess potentially emerging pathogens and disease risks (Appendix C). Basic biometric data (length, weight, Fulton condition factor) are collected by hatchery staff during the fish health examinations. Yearling spring Chinook smolts are forced released from the hatchery into Icicle Creek during the third week of April after 20 months of on-station rearing.

## E. **Coho Salmon program (Yakama Nation)**

The Yakama Nation is conducting a reintroduction program for Coho Salmon in the mid-Columbia River region that includes the Wenatchee River (Yakama Nation 2017). Leavenworth NFH is a partner with the Yakama Nation which contracts with the USFWS to provide culture and administrative support for the project. Each winter, Leavenworth NFH receives yearling Coho Salmon from hatcheries on the lower Columbia River (e.g., Willard NFH, Eagle Creek NFH) for acclimation and 1 – 4 months of rearing prior to release. The Coho Salmon Program is not included in the CCVA presented here.

## F. **Disease history at Leavenworth NFH**

Adult Spring Chinook Salmon at Leavenworth NFH have tested positive for Infectious Hematopoietic Necrosis Virus (IHNV) in multiple years (e.g., as recently as 2018), but juvenile Chinook Salmon at the hatchery have not tested positive for IHNV since 2011. The bacterial pathogens *R. salmoninarum*, *Flavobacterium psychrophilum* (bacterial coldwater disease, BCWD), and *Flavobacterium columnare* (columnaris) are often detected. The parasite *Ichthyophthirius multifiliis* (Ich) is common, occurs annually, and is responsible for significant mortalities in some years (Appendix C).

Adult Coho Salmon tested positive for Viral Hemorrhagic Septicemia Virus (VHSV-IVa) in 2012 and 2013, and for IHNV in 2015. The bacterial pathogens responsible for BKD, BCWD and furunculosis (*Aeromonas salmonicida*) have also been detected. The parasite *Ceratonova shasta* (*C. shasta*) is also present. Juvenile Coho Salmon are often diagnosed with BCWD and the common external parasites *Trichodina sp*. and *Epistylis sp*.

## G. **Fish culture parameters at Leavenworth NFH**

Fish culture guidelines and parameters at Leavenworth NFH are summarized in Table 2.

**Table 2.** Fish culture parameters at Leavenworth NFH.

| Species | Density Index (DI) (Maximum) | Flow Index (FI) (Maximum) | Target release size (fish/lb.) | Target release date | Pathogens / Diseases of concern[a] |
|---|---|---|---|---|---|
| Chinook Salmon | 0.2 | 0.6 | 16 – 20 | Third week of April | Ich, BKD |
| Coho Salmon | 0.2 | 1.0 | 17.5 | First week of April | BCWD, VHSV, IHNV |

[a]BKD (Bacterial Kidney Disease), caused by *Renibacterium salmoninarum.* BCWD (Bacterial Coldwater Disease, caused by *Flavobacterium psychrophilum*. VHSV (Viral Hemorrhagic Septicemia Virus). IHNV (Infectious Hematopoietic Necrosis Virus), caused by *Novirhadovirus spp*.

# 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 Leavenworth NFH and the population of Spring Chinook Salmon propagated there relative to current culture protocols.

## A. **Low surface flows in summer**

Leavenworth NFH is highly sensitive to low surface flows of Icicle Creek during the summer, particularly in August and September (Figure B16). The Icicle-Peshastin Irrigation District (IPID) is the largest water user in the basin (water right of 117 cfs on Icicle Creek) and withdraws an average of 79 – 98 cfs of water upstream of the hatchery during August and September. The City of Leavenworth with a water right of 3 cfs withdraws, on average, an additional 2 cfs at the IPID diversion year round. The Cascade Orchard Irrigation Company has the senior most water right in the basin and withdraws up to 12 cfs at the hatchery intake. In addition, a proposed goal of the Icicle Creek Work Group[13] is to maintain a minimum instream flow of 60 cfs for Icicle Creek adjacent to the hatchery. The hatchery has a water right of 42 cfs for fish culture, thus yielding a total *average* water demand (irrigation, civic, instream, hatchery) on Icicle Creek of approximately 195 – 214 cfs during August and September, values that can exceed total flows during low snow-pack years. Indeed, supplemental releases from Upper Snow Lake provide the vast majority of water available to the hatchery in August and

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

September. Assuming no future reduction in water withdrawals in the Icicle Creek basin, any reduction in total water flows of Icicle Creek or Snow Creek during August and September could significantly affect the ability of Leavenworth NFH to meet its water right of 42 cfs for fish culture.

## B. High water temperatures in summer

Water is first released from Upper Snow Lake at a controlled rate of approximately 45 – 60 cfs during the low flow summer months (August – September) to meet demands at the hatchery or as soon as the temperature of Icicle Creek reaches 14.5 °C at the hatchery intake. As a result, historical mean water temperatures at the hatchery intake during the summer months of July, August and September (14.0 °C, 14.4 °C, and 11.0 °C, respectively; Table B7) have been within the optimum temperature range for juvenile Chinook Salmon (8.6 – 15.9 °C; Table B1). Historical water temperatures for holding and spawning adult salmon for broodstock (7.8 – 9.1 °C, July – September; Table B9) have likewise been within the optimal holding and spawn temperatures of adult Chinook Salmon (9.0 – 12.3 °C; Table B1), due primarily to the use of well water (~9.1 °C) to augment surface flows. Overall, the Spring Chinook Salmon program at Leavenworth NFH is considered less sensitive to potential increases in stream temperatures than decreases in water availability. However, any future decrease in water availability or increase in temperature of water discharged from Snow Lake during the summer would increase the temperature of water available to the hatchery. We thus consider Leavenworth NFH to have moderate sensitivity to higher surface water temperatures during the summer.

## C. Disease risks

Spring Chinook Salmon at Leavenworth NFH are most sensitive to Ich and BKD, two diseases that can become problematic during the summer when water temperatures increase. Historical water temperatures at Leavenworth NFH during the summer are within the minimum disease range for Ich (12 – 15 °C), and Ich outbreaks have occurred in the past resulting in significant mortalities in some years. On the other hand, average water temperatures at Leavenworth NFH during the summer (11.0 – 14.4 °C; Table B7) have been less than the minimum disease temperature for BKD (15 °C; Table B2), and juvenile Chinook Salmon at Leavenworth NFH are considered less sensitive to BKD than to Ich. This lower sensitivity to BKD is due, in part, to aggressive fish health protocols to control BKD via pathogen testing of adult broodstock and segregation/culling of eyed eggs/offspring at high risk of disease. However, if future water temperatures at Leavenworth NFH during the summer approach or exceed 15 °C, then the risks of BKD outbreaks among juvenile Chinook Salmon would increase due to increased stress. We thus consider Spring Chinook Salmon at Leavenworth NFH to have moderate to high sensitivity to disease risks, primarily from higher surface water temperatures.

## D. High surface flows and flood risks

Icicle Creek is largely a snow-driven watershed with highest mean flows historically in May and June during maximum snow-melt discharges (Figure B9). Mean flows during the primary period of precipitation (November – March) have historically been approximately 20 – 25% of the mean flows in May and June. However, two record peak flows occurred on November 29, 1995 and November 6, 2006 when flows reached 19,800 cfs and 14,700 cfs, respectively. Both events were the result of historic rain-on-snow events with some damage to the hatchery infrastructure (Appendix F). The hatchery may be particularly sensitive to rain-on-snow events, although the majority of the hatchery grounds – excluding the fish ladder and water intake structure – are above the flood plain of Icicle Creek. Overall, we consider Leavenworth NFH to have moderate sensitivity to flood risks.

## E. Wildfire risks

Wildfires have been a significant risk at Leavenworth NFH for many years. In August 1994, a large complex of fires – referred to as the "Hatchery Complex" – burned approximately 43,000 acres west of the hatchery, including portions of the Icicle Creek watershed. A secondary effect of this latter fire was large amounts of ash and debris washing down Icicle Creek and into the water intake of the hatchery during the record floods in November, 1995. One of the largest wildfires in Washington State history, the Tyee Fire, burned approximately 144,000 north of the Wenatchee River, also in August 1994. In general, the number and size of summer wildfires along the east slope of the Cascade Mountains have increased in both frequency and size in recent years. As such, the Icicle Creek watershed and Leavenworth NFH are considered to have high sensitivity to wildfire risks, particularly the secondary impacts to water quality at the hatchery.

## F. Sensitivity main points:

- Leavenworth NFH is highly sensitive to low surface flows of Icicle Creek during the summer when juvenile Spring Chinook Salmon are on station and water needs of the hatchery and other users can exceed the total flow volumes available.
- Spring Chinook Salmon at Leavenworth NFH are moderately sensitive to increases in water temperatures during the summer months. This sensitivity is reduced considerably because of cool water discharges from upper Snow Lake.
- Spring Chinook Salmon at Leavenworth NFH have moderate to high sensitivity to disease risk, particularly Ich, as a function of rising surface water temperatures.
- Leavenworth NFH is considered to have moderate sensitivity to flood risks because the majority of the hatchery infrastructure – excluding the fish ladder and water intake structure – are above the flood plain of Icicle Creek. However, the hatchery may be particularly sensitive to rain-on-snow events like those that resulted in record flows of Icicle Creek in the fall of 1995 and 2006.

- The physical facilities and surface water sources for Leavenworth NFH are considered highly sensitive to wildfire risks.

## 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 Leavenworth NFH to climate change in the 2040s are described in Appendix B. Those methods are summarized below.

### A. **Methods**

***Surface water temperatures upstream from Leavenworth NFH***

Outputs from 10 statistically downscaled GCM simulations for the A1B emissions scenario were used to project future air temperatures of the Icicle Creek 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[14] and (b) historic water temperatures of Icicle Creek measured at RM 5.6, approximately 100 meters upstream of the confluence of Snow Creek (Figs. B3, B4; Table B3). That historic relationship between air and water temperature was then used to project future water temperatures of Icicle Creek at RM 5.6 in the 2040s based on projected air temperatures from the 10 GCM models. A regression relationship between water temperatures at RM 5.6 and at the hatchery intake at RM 4.5 was also established based on historic data for those months when water is not released from Snow Lake and assuming a natural hydrograph for Snow Creek.

Water temperatures at the hatchery intake (RM 4.5) were modelled for months when water is released from Snow Lake (August, September) as a simple mixing equation of water temperatures at RM 0.2 of Snow Creek and at RM 5.6 of Icicle Creek, each weighted by their relative historic or projected flows in the 2040s (in cfs). Those calculations also considered the volume of water diverted from Icicle Creek at the IPID diversion at RM 5.8 (Table B4). Two possible scenarios for future temperatures of Snow Creek were analyzed: (1) no change from historic averages and (2) a 2 °C increase from historic averages (see Appendix B for rationales). In aggregate, the presumed 2 °C warming of Snow Creek would be similar to what is projected for Icicle Creek by the 2040s (Appendix B).

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

***Groundwater temperatures***

Exploratory regression analyses revealed no statistical correlation between (a) groundwater temperatures (for both the deep and shallow wells) and (b) surface water temperatures of Icicle Creek at the hatchery intake. Consequently, two feasible scenarios for future groundwater temperatures were analyzed: (1) no change from historic averages for each well category (shallow-well mean = 7.1℃; deep-well mean = 9.1℃), and (2) an increase of 0.25 ℃ from historic values in all months for both well categories.

***Summary of modeled scenarios for future water temperatures in the 2040s***

Future water temperatures in Icicle Creek were modeled directly, as described above, with four potential combination scenarios for future water temperatures of Snow Creek and well water:

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

***Projected water availability at Leavenworth 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 Icicle Creek under the A1B emissions scenario as forced by output from the same ensemble of 10 GCMs used to project future water temperatures (Appendix B). Because of water right and other apportionment issues in Icicle Creek (Table 1), we assumed that the actual quantity of water available to the hatchery from all sources in the future would decrease in direct proportion to any decreases in mean monthly flows estimated by the VIC model for the 2040s. For example, if the Chinook Salmon program currently uses 15 cfs of water on average during a hypothetical month, and the mean flow of Icicle Creek at the hatchery intake for that month was projected to decline by 40% in the 2040s, then the estimated water available to the hatchery from all sources would be 9 cfs (15 cfs × 0.60). These adjustments implicitly assume that all water right users and instream flow requirements would be reduced equally on a proportionate basis in response to reduced future flows as projected from the GCMs and hydrologic model. On the other hand, we assumed that the hatchery cannot use additional water above the mean historic values for months where an increase in mean flow is projected.

## B. Results and Discussion

Climate and hydrologic modeling under the A1B emissions scenario indicate that the Icicle Creek 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 100-year peak flows (Table B5; Figures B5 – B15).

### *Temperature projections*

Mean air temperature over the Icicle Creek watershed is expected to increase in every month (mean increase = 2.0 °C) with the largest absolute increases projected for July – September (range = 2.6 – 3.0 °C; Table B5 and Figure B5). Similarly, water temperature in Icicle Creek at (a) RM 5.6 immediately upstream of its confluence with Snow Creek and (b) at the hatchery intake (RM 4.5) are projected to be warmer in every month in the 2040s compared to the historical period (Table B7; Figures B17 and B18). At RM 5.6, mean annual water temperature is projected to increase by 1.3 °C with increases of more than 2 °C during July, August, and September. Virtually identical increases are projected at RM 4.5 at the hatchery intake except during August and September when coldwater releases from Snow Lake result in temperature increases of only 1.5 °C and 1.1 °C, respectively assuming no water is diverted at the IPID diversion at RM 5.8 (Table B8; Figure B18a). If water continues to be diverted at the IPID diversion in the 2040s at current rates, then water temperatures for Icicle Creek at the hatchery intake in August and September are projected, paradoxically, to be less than historical averages under Scenarios A and B (no increase in temperature of Snow Creek). This latter decrease in projected water temperature at the hatchery intake during August and September occurs because of lower projected flows of Icicle Creek upstream of the confluence of Snow Creek with a consequentially greater proportional contribution of cool water from Snow Creek assuming no change in the quantity of water released from Snow Lake in the 2040s.

### *Precipitation projections*

Mean monthly precipitation is projected to show little change from the historical average in the 2040s (historical: 142 mm, 2040s: 150 mm; Table B5; Figure B6). Icicle Creek currently has a snowmelt-driven hydrology, but the 10 GCMs projected a 28% reduction in mean peak snow water equivalent (SWE) for April in the 2040s (historical peak mean = 784 mm; 2040s peak mean = 562 mm) with a 35% overall reduction in mean monthly snowpack (Table B5; Figure B7). In short, substantially more precipitation is expected to fall as rain and less as snow in the 2040s with only a slight increase in total annual precipitation.

### *Hydrographic projections*

Mean *annual* flows for Icicle Creek in the 2040s are projected to be similar or slightly higher than the modeled historical values (historical = 600 cfs, 2040s ensemble mean = 635 cfs; Table B6). However, the shape of the hydrograph for the 2040s was projected to be quite different from the historic average, with higher flows in late fall and winter, lower peak flows in June, and consistently lower flows in summer (Figures B9 – B15). Mean flows of Icicle Creek at Leavenworth NFH in the 2040s were projected to increase by an average of 76.9% (ensemble range 62 – 108%) in the late fall and winter (November – March) and decrease by an average of

42.5% (ensemble range -18.9% to -67.8%) in summer (June – September) (Figures B9 and B10). The magnitude of 100-year peak flows (Q100 statistics) in the vicinity of Leavenworth NFH, presumed to occur in late fall and winter (Appendix B), is projected to increase by over 50% from approximately 9,500 cfs to approximately 15,000 cfs (12,000 – 21,000) in the 2040s (Figure B15 and B16). Similarly, summer low flow events (7Q10 statistics) are projected to be more severe across much of the basin (Figures B12 and B13).

The modeled hydrography for the 2040s suggests that, on average, substantially less water will reach the intake for the hatchery during June – September compared to the historical time period (1915 – 2006). If the current rates of surface water diversion at the IPID diversion structure continue into the 2040s without additional inflow and/or storage during the spring, then Icicle Creek immediately downstream from the IPID diversion would most likely be dewatered (or nearly so) in August and September of every year, and the only surface water source for the hatchery would be water flows from Snow Creek. Under these latter conditions, projected water flows from Snow Creek would barely meet the 42 cfs water right of the hatchery assuming no future increase in water availability from Upper Snow Lake. However, 100% of the water released from Upper Snow Lake during August and September in the 2040s would need to remain in Icicle Creek to achieve the proposed instream flow goal of 60 cfs adjacent to the hatchery. These hydrology projections, primacy water rights of other users, and instream flow goals raise questions regarding the future availability of surface water to the hatchery during August and September.

In a broad sense, our modelled projections reflect the transition of the Icicle Creek basin from largely a snow-melt driven watershed historically to a mixed rain-and-snowmelt driven watershed by the 2040s. As such, flood risks in the late fall and winter are expected to increase, particularly during rain-on-snow events. Summer drought conditions are expected to also increase because of reduced snow pack and lower base flows.

## C. **Exposure main points:**

- Surface water temperatures of Icicle Creek are expected to be warmer in all months with mean annual water temperatures at RM 5.6, immediately upstream of the confluence of Snow Creek, projected to increase by 1.3 °C and increase by more than 2 °C during July, August, and September.
- Total annual and mean monthly precipitations in the 2040s for the Icicle Creek basin are projected to be largely unchanged from historic values but substantially more precipitation will fall as rain and less as snow with a projected 35% reduction in mean monthly snowpack.
- Mean *annual* flows projected for Icicle Creek in the 2040s will be similar or slightly higher than the modeled historical values, but the shape of the hydrograph for the 2040s was projected to be quite different from the historic average with higher flows in late fall and winter, lower peak runoff in June, and consistently lower flows in summer. Indeed,

if water withdrawals upstream of the hatchery for irrigation continue at current rates, then Icicle Creek between the IPID diversion and the confluence of Snow Creek would most likely be dewatered during August and September.

- Water releases from Snow Lake in August and September are projected to be barely sufficient in the 2040s to meet the 42 cfs water right of the hatchery. However, a proposed goal to maintain a minimum instream flow of 60 cfs adjacent to the hatchery may preclude withdrawal of any water by the hatchery during the summer if water continues to be diverted upstream of the hatchery at current rates for irrigation.
- The Icicle Creek basin will most likely transition from a historical snowmelt-driven watershed to a mixed snow-and-rain-driven watershed in the 2040s with substantial increases in peak flows in late fall and winter, particularly during rain-on-snow events.

## 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 Leavenworth NFH, we first addressed the following question: Could the current Spring Chinook Salmon program continue to operate successfully, according to existing schedules and protocols, under the climatic conditions projected for the Icicle Creek watershed in 2040s? To address this question, we focused primarily on 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 environmental conditions are likely to preclude culture of Spring Chinook Salmon at Leavenworth NFH, and (b) identify the magnitude and timing of sub-lethal effects (altered growth rates, disease risks, etc.) that may affect survival and growth of Spring 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 for each month of the freshwater hatchery phase as a function of projected water temperatures in the 2040s, assuming an unlimited food ration. The growth model was implemented for five modeled scenarios: (a) recent historical conditions and (b) the four future water temperature scenarios (A, B, C, and D) described previously for the 2040s. 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 Spring 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).

## B. **Results and Discussion**

### ***Spring Chinook Salmon program***

Adult Chinook Salmon returning to Leavenworth NFH are typically captured for broodstock from mid-May to early July and retained in holding ponds prior to spawning in early September. These ponds are supplied with a mix of groundwater and surface water from Icicle Creek until spawning. By the 2040s, water temperatures in the holding ponds during May through September are projected to increase by 0.0 – 1.1 °C with the highest temperature (11.2 °C) occurring in June (Scenarios B and D; Table B9; Figure B19). Those projected mean temperatures in the 2040s do not exceed the optimal spawning temperatures for Chinook Salmon (5.7 – 11.7 °C; Table B1). Consequently, adult Chinook will most likely not experience physiological stress during holding and spawning due solely to temperature.

Fertilized eggs are incubated on 100% well water, and projected future water temperatures under all four scenarios (7.1 – 9.4 °C; Table B9) do not exceed the optimal egg incubation temperatures for Chinook Salmon (8.4 – 12.4 °C; Table B1).

Juvenile Chinook Salmon reared at Leavenworth NFH will be exposed to warmer rearing conditions in all months in the 2040s with projected temperature increases ranging from 0.1 °C to 2.1 °C across the rearing periods (August year 1 to April year 2; Table B9, Figure B18). Projected water temperatures during the juvenile growth phase in the 2040s do not exceed the upper optimum for Chinook Salmon (15.9 °C ; Table B1) except during July (16.4 °C), assuming water is not released from Snow Lake prior to August 1. Higher water temperatures during the summer are expected to increase disease risks, particularly for Ich. Disease risks may be further exacerbated in the future by improved passage of adults upstream of the hatchery. Projected water temperatures in April (5.7 °C; Table B9) when smolts are released are well below the upper limit for proper smoltification (14.0 °C; Table B1).

Under current culture protocols, the total biomass of Spring Chinook Salmon at Leavenworth NFH would likely exceed fish health guidelines for the hatchery by the 2040s. Warmer water temperatures projected for the 2040s will increase growth rates and total biomass of juvenile Chinook Salmon under all four modeled scenarios assuming no change in the number of fish reared (Table B10). For example, under Scenario A (no increase in temperatures of well water and Upper Snow Lake), mean weight and length of Chinook Salmon smolts at release are projected to be 24.8% and 7.8% higher, respectively, than mean sizes historically assuming no culture modifications or compensatory biological responses (e.g., precocious sexual maturation that reduces growth). Under Scenario D (2 ℃ warming of Upper Snow Lake and 0.25 ℃ warming of well water), Chinook Salmon smolts from Leavenworth NFH are projected to be, on average, 35.9% heavier and 10.6% longer at release compared to historic sizes.

Flow index values for Spring Chinook Salmon at Leavenworth NFH have fluctuated historically around the fish health guideline value of 0.6 during the last eight months of rearing (September – April) but have consistently exceeded the guideline value only in April immediately prior to release (Table B11A; Figure B21). Increased fish growth in response to warmer temperatures in the 2040s will cause flow index values to consistently exceed the threshold value of 0.6 during the last eight months of the rearing cycle (Table B11B; Figure B21a). Density index values are also projected to increase relative to the historic average and approach the threshold guideline value of 0.2 by April of the second year (Table B11B; Figure B21b). These projected density and flow index values would increase disease risks for Ich and BKD assuming that the same number of fish are reared. These projected density and flow index values are considered conservative because they (a) are based strictly on temperature, (b) assume no changes in water availability, and (c) do not account for the biological effects of reuse water in raceways.[15]

Although projected water temperatures at Leavenworth NFH in the 2040s are expected to be compatible with the physiological requirements of Spring Chinook Salmon, the quantity of water available to the hatchery during the irrigation season may preclude the ability of the hatchery to maintain any fish on station during the summer months under current water allocation paradigms. Projected water flows of Icicle Creek both upstream and downstream of the confluence of Snow Creek are barely sufficient to meet historical water withdrawals for irrigation and the proposed 60 cfs instream flow goal of Icicle Creek adjacent to the hatchery, thus potentially precluding the availability of any surface water for the hatchery and bypass channel during the summer months.

***Hatchery infrastructure***

A significant increase in the magnitude of 100-year peak water flows (Q100 statistics) from approximately 9,500 cfs historically to 15,000 cfs in the 2040s (Figure B15) raises many questions regarding future flood risks to Leavenworth NFH, especially during anticipated rain-on-snow events. As noted previously, a record peak flow of Icicle Creek (19,800 cfs) occurred on November 29, 1995 following an "atmospheric river" rain-on-snow event. The Q100 projections suggest that the likelihood of similar flows in excess of 15,000 cfs will increase in

[15] During February through April (year 1 of the salmon life cycle), Leavenworth NFH typically uses a serial water reuse strategy in a gravity-feed, tiered raceway structure where juvenile Chinook Salmon in "downstream" raceways receive 50% of their water as effluent from upstream raceways with the remainder a blend of fresh well (45%) and surface (5%) water (Table B9). During December through April of their second year (until release), fish are again subjected to serial reuse after they are moved to adult ponds (see Figure B21) such that 28% of their water supply is "second pass" reuse water and 72% is fresh surface water. Reduced water quality associated with reuse water increases the *effective* density and flow indices via reduced dissolved oxygen and increased concentration of metabolites (e.g., ammonia), but no accepted way exists currently to quantify those effects mathematically relative to fish-health guidelines.

the future. We defer to USFWS hydraulic engineers and hatchery staff to assess potential future impacts to hatchery infrastructure when peak flows of Icicle Creek exceed 15,000 cfs.

Reduced snowpack and less precipitation during the summer in the 2040s are expected to increase wildfire risks to Leavenworth NFH. Indeed, the incidence of wildfires in eastern Washington has increased significantly since the 1980s.[16] A primary indirect effect of wildfires is high siltation and debris loads that significantly decrease water quality, increase disease risks to fish on station, and potentially cause damage to the hatchery infrastructure.

### C. **Impact main points:**

- Higher water temperatures alone in the 2040s are not expected to preclude the ability of Leavenworth NFH to propagate Spring Chinook Salmon. However, faster growth rates due to higher water temperatures will result in greater total biomass of fish at the time of release with flow index values exceeding the fish health guideline of FI < 0.6 during the last eight months of the rearing cycle assuming that the current number of fish reared on station remains unchanged.
- Higher water temperatures projected for the 2040s during the summer months will likely increase disease risks, particularly for Ich.
- Significant reductions in the future availability of surface water during the summer months raise questions regarding the ability of Leavenworth NFH to maintain fish on station during August and September in the 2040s. After accounting for irrigation withdrawals upstream of the hatchery and the desire to maintain a minimum instream flow of 60 cfs adjacent to the hatchery, virtually no surface water would be available for fish culture during August and September in the 2040s.
- Transition of the Icicle Creek watershed from primarily a snow-driven watershed historically to mixed rain-snow-driven watershed in the 2040s is expected to significantly increase flood risks in the late fall and winter and wildfire risks during the summer. However, we did not model or assess those risks directly but defer to USFWS hydraulic engineers and hatchery staff to assess the impacts associated with higher flood and wildfire risks in the 2040s.

## 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.*

---

[16] Fires that burned more than 5,000 acres in Washington State are compiled at: https://en.wikipedia.org/wiki/List_of_Washington_wildfires . The three largest wildfires in Washington State history have occurred since 2014.

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 met with the Hatchery Evaluation Team (HET) for Leavenworth NFH on September 2, 2021 to discuss the adaptive capacity of Leavenworth NFH to reduce the projected climate change impacts to the hatchery and Spring Chinook Salmon program in the 2040s (Appendix D). The purposes of the meeting were: (a) assess the current ability or adaptive capacity of Leavenworth NFH to maintain the 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 Leavenworth 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 Leavenworth NFH and its programs to adapt to the projected impacts of climate change.

## B. **Results and Discussion**

***Spring Chinook Salmon program***

1. ***Impact:*** Spring Chinook Salmon in the 2040s will grow faster due to higher mean water temperatures resulting in density and flow index values that will approach or exceed fish health guidelines. Although higher water temperatures alone in the 2040s are not expected to preclude the ability of Leavenworth NFH to propagate Spring Chinook Salmon, the mean weight and length of Chinook Salmon smolts at release are projected to be 24.8% and 7.8% greater in the 2040s than historically (Scenario A). Higher flow and density index values are expected to increase disease risks, particularly for Ich and BKD (Appendix C).

   ***(a) Infrastructure adaptations***:

   - A prototype Partial Reuse Aquaculture System (PRAS) is currently being tested at Leavenworth NFH to address the likelihood of reduced water availability during the summer (Cutting and Whitbeck 2017). A fully-developed PRAS with chillers would theoretically be able to maintain water temperatures and growth rates within desired parameters.
   - An incubation chiller is currently used during egg development. Further delaying hatch and emergence of fry, by increasing chiller capacity or increasing the duration of use, would decrease the length of the growth-rearing cycle and could help compensate for faster growth rates.

***(b) Protocol and management adaptations:***

- At the present time, the primary strategy for reducing water temperatures during the summer is with coldwater releases from Upper Snow Lake and use of available groundwater resources. Hatchery staff will continue to maintain and use groundwater resources to modify water temperatures.
- Proactive disease-preventive medicine will continue to be emphasized in the future to reduce the likelihood of disease outbreaks and the need for reactive treatment approaches (e.g., antibiotics to treat bacterial diseases).
- Feeding schedules could be adjusted to reduce growth rates, if desired.
- The undesired incidence of precocious maturation, often associated with faster growth rates in captivity, will be closely monitored by hatchery and fish health staff.

2. ***Impact:*** Higher water temperatures projected for the 2040s will increase disease risks to both juvenile and adult Spring Chinook Salmon at Leavenworth NFH, particularly for Ich during the summer months. Disease risks may be exacerbated by improved upstream passage of adults in Icicle Creek upstream of the hatchery and the water intake.

***(a) Infrastructure adaptations:***

Adaptive measures identified by the HET would require significant investments in hatchery infrastructure. Those measures are listed below.

- Development of a full-scale PRAS equipped with biofilters, UV disinfection and chillers would be expected to reduce disease risks to juvenile Chinook Salmon.
- Enlargement of the adult holding pond would reduce fish densities and disease risks to adult broodstock prior to spawning.
- Construction of a direct water line from the hatchery intake pipe to the adult holding pond would increase water quality and reduce disease risks. Currently, water supplied to the adult holding pond is 3$^{rd}$-pass serial reuse water from the raceways.

***(b) Protocol and management adaptations:***

- Fish culture activities involving direct handling of fish could be restricted to early morning hours when water temperatures are lowest.
- Continued emphasis of proactive disease-preventive medicine, as described previously under Impact #1, would reduce disease risks. These proactive measures include early intervention and treatment in response to the first clinical signs of disease.

3. ***Impact:*** Significant reductions in the availability of surface water from Icicle Creek during the summer months in the 2040s will likely preclude the ability of Leavenworth NFH to maintain juvenile Spring Chinook Salmon on station in August and September if

water is retained in Icicle Creek to meet the proposed minimum 60 cfs instream flow goal.

***(a) Infrastructure adaptations:***

- The Icicle Creek water intake for Leavenworth NFH is scheduled to be reconstructed in 2023. In addition, the Cascade Orchards Irrigation Company (COIC) – which currently withdraws approximately 7 cfs of water at the current intake for the hatchery – is planning to construct a new water intake in lower Icicle Creek downstream of the hatchery, thus saving an additional 7cfs of flow upstream of the hatchery. When that new COIC intake is constructed, the current open ditch to the hatchery intake will be replaced by a pressurized pipe which is expected to save several additional cfs of water towards meeting the proposed 60 cfs instream-flow goal.
- Installation of infrastructure to allow automated control of the outlet valve for upper Snow Lake is highly desired and currently on the new projects list for Leavenworth NFH. The current system requires a person to physically hike to Upper Snow Lake, approximately a 5,000-foot elevation gain, to adjust the valve manually when needed. An automated valve would allow water to be released on demand, thus reducing total withdrawals and allowing the hatchery to conserve storage water in Upper Snow Lake during the summer.
- As noted above, a pilot PRAS is currently being developed and tested at Leavenworth NFH. A full build-out of the PRAS is predicted to reduce water needs of the hatchery by approximately 50% during the summer, from ~ 45 cfs to 20 – 25 cfs. If the pilot project proves successful and the system is expanded to full build-out, then the hatchery would be able <u>to reduce water withdrawals from Icicle Creek by up to 20 cfs.</u>
- Automation of the outlet valves, as proposed for upper Snow Lake, are highly desired also for four IPID reservoirs in the upper Icicle Creek watershed. At the present time, the outlet valves for the four IPID reservoirs must be adjusted manually, similar to the outlet valve for upper Snow Lake. Evaluations by the Icicle Work Group suggest that both the water needs of Leavenworth NFH and the 60 cfs instream-flow goal can be achieved if release waters from the four IPID reservoirs and Upper Snow Lake are controlled remotely in response to availability and demand. Reconstruction of the outlet structures of the four IPID storage lakes with radio-controlled valves is expected to reduce water withdrawals by 10 – 15 cfs.

***(b) Protocol and management adaptations:***

- Groundwater is used extensively to supplement surface water in the raceways and adult holding pond. Maintaining the groundwater infrastructure is a high priority.

- The Icicle Creek Work Group has proposed much work that will indirectly help the hatchery to meet its water needs in the 2040s.

***Hatchery infrastructure***

1. ***Impact:*** Transition of the Icicle Creek watershed from primarily a snow melt-driven watershed historically to a mixed rain-and-snow-driven watershed in the 2040s is expected to increase flood risks in the late fall and winter. For example, the magnitude of 100-year peak water flows (aka 100-year floods) is projected to increase from approximately 9,500 cfs historically to 15,000 cfs in the 2040s. Leavenworth NFH appears to be fairly well buffered from the direct impacts of floods because most of the hatchery infrastructure is above the flood plain of Icicle Creek. However, the current water intake structure, the adult holding ponds and ladder, and the pollution abatement pond are susceptible to high water events and floods. These structures were impacted significantly by high water events in 1995 and 2006. Overall, the biggest threat of high surface flows could be high sediment loads and fine debris in the intake water that increase disease risks to fish on station.

   ***(a) Infrastructure adaptations:***

   - A new water intake structure is scheduled for construction in 2023, and the engineering design of the new structure considered the 1995 record flow of 19,800 cfs.
   - Hatchery staff noted that the adult ponds and ladder – as configured currently – are vulnerable to very high flows of Icicle Creek (Appendix D). They also noted the need to reconfigure and expand the size of the adult ponds to reduce fish densities and disease risks, primarily for Ich, before surplus fish are provided to the Tribes during the broodstock holding period. However, extremely high flows of Icicle Creek in the future would, most likely, not directly affect adult Chinook Salmon because they would not be in the ponds in the late fall and winter when projected peak flows are expected.
   - Disease risks to juvenile fish on station during peak flows of Icicle Creek would be reduced if development of a PRAS for the hatchery allowed closure of the surface water intake during high sediment flows.

   ***(b) Protocol and management adaptations:***

   - None identified.

2. ***Impact:*** Higher mean air temperatures during the spring and summer, coupled with reduced spring snow pack and decreases in mean summer precipitation, are expected to increase wildfire risks to the Icicle Creek watershed and Leavenworth NFH through the 2040s.

   ***(a) Infrastructure adaptations:***

- Fire at the hatchery is not as big of a concern as mud, ash and debris washing into Icicle Creek from the upper watershed where major fires have occurred in the past. Leavenworth NFH has had several inches of mud and debris in raceways that washed down from the upper watershed following fires. The existing settling basin will help reduce sediment loads in the intake water. In addition, as noted previously, development of a full-scale PRAS may allow closure of the surface water intake during high flows with large sediment loads.
- The hatchery maintains a diesel-powered electric generator that would mitigate loss of electricity due to a fire or other causes.

***(b) Protocol and management adaptations:***

- Hatchery staff believe that the buildings and infrastructure of Leavenworth NFH are well buffered against the direct effects of potential wildfires. For example, all major building have metal roofs. Several staff at Leavenworth NFH are former fire crew members, and they keep the hatchery manager informed about fire risks and the measures necessary to minimize those risks and potential impacts.
- Leavenworth NFH is adjacent to National Forest lands. Many partnerships dealing with fire management in the Icicle Creek and Wenatchee River watersheds are present. Hatchery staff work with the Fire Management Officer to develop land management and burn plans for timber and slash piles that reduce wildfire risks. In the past, the grounds of Leavenworth NFH have served as a U.S. Forest Service base camp for firefighters during active fires.

## C. **Adaptive Capacity main points:**

- Higher disease risks associated with warmer water temperatures in the 2040s will be controlled primarily through proactive preventive medicine with treatments implemented as needed at first detections of clinical disease. Potential future development of a partial reuse aquaculture system (PRAS) would be expected to further reduce disease risks through UV disinfection and the potential use of chillers. Enlargement and reconfiguration of the adult holding pond are desired to reduce fish densities and provide first-pass surface water rather than 3$^{rd}$ pass reuse water to adults prior to spawning or surplusing to the Tribes.
- Leavenworth NFH currently has very limited capacity to adapt to the lower summer flows of Icicle Creek projected for the 2040s. Under the existing hatchery infrastructure, little or no surface water is projected to be available for fish culture at Leavenworth NFH during August and September in the 2040s if current withdrawals by other users and the proposed goal of a minimum instream flow of 60 cfs for Icicle Creek are maintained. However, several infrastructure improvements have been proposed that would help conserve surface water availability during the summer (e.g., development of a full-scale PRAS, automation with remote control of the existing manual valve on the outlet of

Upper Snow Lake, improved irrigation efficiencies and water conservation efforts, automation of other storage water resources, etc.).

- Leavenworth NFH appears to have little adaptive capacity at the present time to avoid high siltation and potential damage to the water intake structure, adult holding pond, and fish ladder during peak flows (> 15,000 cfs) projected for the 2040s. Those structures were damaged or severely impacted during the record peak flow (19,800 cfs) of Icicle Creek in November, 1995. However, a new water intake structure is scheduled for construction in 2023, and potential development of a full-scale PRAS would likely allow closure of the water intake during high siltation loads, thus protecting the hatchery infrastructure from siltation and reducing disease risks to juvenile fish on station.
- Hatchery staff consider Leavenworth NFH to be well buffered from the direct effects of future wildfires that will most likely increase in frequency in the 2040s and beyond. Most of the main buildings are covered with metal roofs, and fire protection measures are in place. The primary risk to the hatchery may be post-fire ash and sediment washing down from the upper Icicle Creek watershed and entering the water intake system of the hatchery following major wildfires.

## 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. **Spring Chinook Salmon Program**

The Spring Chinook Salmon Program at Leavenworth NFH appears to be highly vulnerable to the future impacts of climate change projected for the 2040s. This vulnerability is due primarily to an insufficient quantity of surface water from Icicle Creek projected for the 2040s during August and September when juvenile Chinook Salmon are on station. In addition, disease risks are expected to increase because of warmer water temperatures and correlated factors (e.g., faster growth rates) without existing capacity to mitigate those higher risks other than implementing preventive fish health medicine and intensive fish health monitoring. In the short term, those disease risks could be reduced by reducing the number of fish reared on station. However, projected shortages of surface water in the 2040s during the summer and early fall would eventually preclude maintaining juvenile fish on station year round if the proposed 60 cfs minimum instream flow is maintained. Implementation of several adaptive measures in the future would likely allow the Spring Chinook Salmon program to continue through the 2040s including (a) automation of manual outlet values for Upper Snow Lake and four IPID reservoirs in the upper Icicle Creek watershed, thus allowing conservation of water via real-time adjustments of flows in response to need and environmental conditions, and (b) full build-out of a PRAS, the feasibility of which is currently being tested with a pilot PRAS. Not only would those two adaptive measures conserve a very significant amount of Icicle Creek water, but the potential ability to chill and disinfect recirculated water would also reduce disease risks. Enlargement of the adult holding pond and construction of a direct water line from the Icicle Creek intake line to the adult holding pond are adaptive measures that would reduce disease risks and the future vulnerability of trapped adults held for broodstock.

## B. **Hatchery infrastructure**

The primary climate change threats to the hatchery infrastructure are floods and wildfires.

The hatchery appears to be only moderately vulnerable to flood risks because the majority of the hatchery infrastructure is above the flood plain of Icicle Creek. However, the water intake structure and the adult fish ladder sustained damage from extremely high flows of Icicle Creek in 1995 and 2005, and those vulnerabilities still exist. The water intake structure on Icicle Creek is scheduled for replacement in 2023 with a new design that considered the record flood in November 1996 (19,800) cfs. The new intake structure is expected to reduce vulnerabilities from future floods and high flows considerably.

Although warmer-drier summers will most likely increase wildfire risks through the 2040s (and beyond), hatchery staff believe the facilities are well buffered from the direct effects of wildfire because of active management and ongoing precautionary measures to reduce those risks (Appendix D). As such, the vulnerability of Leavenworth NFH to the direct effects of wildfire may be low. The biggest vulnerability of Leavenworth NFH to future wildfires may be the resulting ash, sediments and debris that wash down Icicle Creek following a major fire event in the watershed. Those suspended solids and combustion byproducts pose disease risks to fish on station. A fully developed PRAS in the future, if built, may be able to mitigate those future impacts if a PRAS would allow closure of the Icicle Creek intake to the hatchery during periods of high sediment loads.

## C. **Vulnerability main points:**

- The Spring Chinook Salmon Program at Leavenworth NFH is highly vulnerable to lower surface water availability from Icicle Creek in the 2040s, primarily during August and September when projected water flows at the hatchery intake may be insufficient to meet the 42 cfs water right of the hatchery. Indeed, the projected shortage of water in August and September will most likely preclude the ability of Leavenworth NFH to maintain juvenile Chinook Salmon on station year round without major infrastructure adaptations (e.g., development of a full-scale PRAS), particularly if instream flows of Icicle Creek adjacent to the hatchery are maintained at proposed levels (minimum 60 cfs).
- Disease risks and vulnerabilities of juvenile and adult Spring Chinook Salmon are expected to increase with increasing water temperatures in the 2040s. Ich and BKD are the diseases of greatest concern. The adaptive measures available currently to mitigate those risks are primarily preventive medicine and proactive fish health monitoring.

- Leavenworth NFH appears to be only moderately vulnerable to future floods and higher peak flows of Icicle Creek projected for the 2040s because the majority of the hatchery infrastructure (buildings, raceways) is above the flood plain. However, the water intake structure and fish ladder have been significantly impacted in the past from very high peak flows, and those vulnerabilities continue. The water intake structure on Icicle Creek is scheduled to be replaced in 2023 with a new design that considered the highest peak flow recorded in Icicle Creek (19,800 cfs). Completion of the water intake project is expected to reduce flood vulnerabilities considerably.
- Although the wildfire risks are expected to increase in the future because of warmer-drier summers, the vulnerability of Leavenworth NFH to the direct effects of wildfire are considered comparatively low because of proactive management by hatchery staff to buffer the hatchery from those risks. The greatest vulnerability of Leavenworth NFH to future wildfires may be the indirect impacts of ash and suspended sediments that are washed down the watershed during high water events and enter the water intake structure of the hatchery, thus posing an additional health risk to fish on station.

## 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 temperature and flow impacts to the *migration corridor* of the Columbia and Wenatchee rivers, from the Pacific Ocean to Icicle Creek, 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 and other regions of the Pacific Northwest to propagate Pacific salmon and Steelhead through the 21st Century. Details regarding these uncertainties are described in Appendix F.

## XI. CONCLUSIONS

1. Higher water temperatures alone will not preclude the ability of Leavenworth NFH to propagate Spring Chinook Salmon in the 2040s. However, disease risks are expected to increase, particularly for Ich and BKD, because of higher water temperatures and faster fish growth rates with a consequential increase in flow and density index values. Those latter index values are projected to approach or exceed the upper limit of fish health guidelines, assuming no changes in infrastructure or the number of fish reared.
2. Significant decreases in surface water flows of Icicle Creek during the summer months may preclude the ability of Leavenworth NFH to maintain fish on station during August and September in the 2040s. Virtually no surface water would be available for fish culture in August and September if the proposed minimum instream flow goal of 60 cfs is achieved. Alternatively, Icicle Creek would most likely be dewatered, or nearly so,

between the hatchery intake and the hatchery outflow in the 2040s if the hatchery exercised its full 42 cfs water right.

3. The Icicle Creek watershed will transition from primarily a snowmelt-driven watershed historically to a mixed rain-and-snowmelt-driven watershed by the 2040s. This transition will significantly increase peak flows of Icicle Creek in the late fall and winter with a commensurate increase in flood risks. Those hydrology projections for the 2040s suggest a higher likelihood of major impacts to the hatchery infrastructure because of increases in the magnitude and/or frequency of extreme high water events.
4. Higher mean air temperatures, reduced snow pack, and lower surface water flows throughout the Icicle Creek watershed in summer will further increase wildfire risks in the 2040s. A major indirect impact of wildfire is reduced water quality from ash and silt in surface waters that can impact fish health following major storm events.

# XII. RECOMMENDATIONS

1. Continue testing a prototype partial reuse aquaculture system (PRAS) at Leavenworth NFH. If considered feasible, design a full-scale PRAS capable of supporting the current Spring Chinook Salmon program during the summer and early fall when the quantity of surface water available from Icicle and Snow Creeks may be insufficient for maintaining Chinook Salmon on station.
2. Install infrastructure to automate the current manual valve on the outlet pipe for upper Snow Lake to allow real-time remote operations of the valve.
3. Continue to support automation of the control valves on the outlets of the four IPID reservoirs in the upper Icicle Creek watershed.
4. Develop a contingency plan for transferring all or a portion of Spring Chinook Salmon juveniles from Leavenworth NFH to another hatchery or location during the summer months in the event that the quantity of surface water available for fish culture is not sufficient for maintaining an entire brood year of fish. A similar contingency plan may exist currently at Warm Springs NFH. Future development of a full-scale PRAS at Leavenworth NFH and/or implementation of recommendations #2 and #3 may obviate the need for developing the contingency plan recommended here.
5. Reconfigure and enlarge the adult collection and holding ponds to reduce fish densities and the risk of disease to adult Chinook Salmon held on station prior to spawning and/or surplusing to the Tribes.
6. As part of recommendation #5 or during construction of the new Icicle Creek water intake structure scheduled in 2023, construct a direct water supply line from the new water intake pipe/structure to the adult holding ponds to provide fresh, first-pass water to

adult Chinook Salmon held for broodstock. This measure will increase water quality and reduce disease risks.

7. Continue to maintain groundwater infrastructure and well-rehabilitation activities.
8. Investigate additional groundwater options and infrastructure upgrades to increase the quantity of groundwater available during the summer.
9. Continue working through the Icicle Work Group to develop a Decision Support Tool for water management of Icicle Creek.
10. Solicit a hydrologist and/or engineer to assess future flood risks and potential damage to the hatchery infrastructure during a future 100-year peak flow of Icicle Creek that could approach or exceed 20,000 cfs in the 2040s. Based on that hydrology assessment, implement measures deemed necessary to protect highly vulnerable areas of the hatchery infrastructure (e.g., fish ladder, settling pond) in the event of a major episodic flood event.
11. Update the Station Safety Plan and ensure all possible measures to reduce wildfire risks are in place.

# XIII. REFERENCES[17]

Abdul-Azia, O.I., N. J. Mantua, and K.W. Myers. 2011. Potential climate change impacts on thermal habitats of Pacific salmon (*Oncorhynchus* spp.) in the north Pacific Ocean and adjacent seas. Canadian Journal of Fisheries and Aquatic Science 68:1660-1680.

Belchik, M., D. Hillemeier, and R.M Pierce. 2004. The Klamath River Fish Kill of 2002: Analysis of Contributing Factors. Final Report, No. PCFFA-155. Yurok Tribal Fisheries Program, Yurok Nation. 42pp. Available at: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/PCFFA&IGFR/part2/pcffa_155.pdf.

*Caudill, J. 2002. The Economic Effects of Pacific Northwest National Fish Hatchery Salmon Production: Four Mid-Columbia River Hatcheries. U.S. Fish and Wildlife Service, Division of Economics. 75 pp.

*Cutting, B., and D. Whitbeck. 2017. Leavenworth National Fish Hatchery Recirculating Aquaculture System Feasibility Study. Engineering Report, MWH Engineering (Stantec). 86pp.

California Department of Fish and Game (CDFG). 2004. September 2002 Klamath River Fish-Kill: Final Analysis of Contributing Factors and Impacts. California Department of Fish and Game, Northern California-North Coast Region, The Resources Agency, State of California, Sacramento, California. 173 pp.

Dawson, T P., S.T. Jackson, J.I. House, I.C. Prentice, and G.M. Mace. 2011. Beyond predictions: biodiversity conservation in a changing climate. Science 332:53-58.

*Elsner, M.M., L. Cuo, N. Voisin, J. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S. Lee, and D.P. Lettenmaier. 2010. Implications of 21st century climate change for the hydrology of Washington State. Climatic Change 102(1-2):225-260.

Guillen, G. 2003. Klamath River Fish Die-off, September 2002: Report on estimate of mortality. Report No. AFWO-01-03, U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata, California. 35pp. Available at: https://www.fws.gov/arcata/fisheries/reports/technical/Klamath_River_Dieoff_Mortality_Report_AFWO_01_03.pdf .

*Hanson, K.C., and K.G. Ostrand. 2011. Potential effects of global climate change on National Fish Hatchery operations in the Pacific Northwest, USA. Aquaculture Environment Interactions 1:175-186.

Harvell, D., S. Altizer, I.M. Cattadori, L. Harrington, and E. Weil. 2009. Climate change and wildlife diseases: When does the host matter the most? Ecology 90:912-920.

[17] Reference preceded by an asterisk (*) are cited in the report.

Hoegh-Guldberg, O., and J.F. Bruno. 2010. The impact of climate change on the world's marine ecosystems. Science 328: 1523-1528.

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

*Independent Scientific Advisory Board (ISAB). 2007. Climate change impacts on Columbia River Basin Fish and Wildlife, May 11, 2007. Available at: http://www.nwcouncil.org/library/isab/ISAB%202007-2%20Climate%20Change.pdf .

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

*Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team: R.K. Pachauri and L.A. Meyer (eds.), Geneva, Switzerland. 151 pp. Available at: https://www.ipcc.ch/report/ar5/syr/ .

Irvine, J.R., and M.-A. Fukuwaka. 2011. Pacific salmon abundance trends and climate change. ICES Journal of Marine Science. 68:1122-1130.

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

*Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, and R.L. Wingate. 2010. Rising stream and river temperatures in the United States. Frontiers in Ecology and the Environment 8:461-466.

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

*Lichatowich, H.A., and J.D. McIntyre. 1987. Use of hatcheries in the management of Pacific anadromous salmonids. American Fisheries Society Symposium 1:131-136

*Luce, C.H., and Z. Holden. 2009. Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. Geophysical Research Letters 36, L16401.

Mantua, N.J. 2009. Patterns of change in climate and Pacific salmon production. Pages 1143-1157 in: Krueger, C.C., and C.E. Zimmerman (editors), Pacific Salmon: Ecology and Management of Western Alaska's Populations. Symposium 70, American Fisheries Society, Bethesda, MD.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and F.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.

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

Marcogliese, D.J. 2008. The impact of climate change on the parasites and infectious diseases of aquatic animals. Revue scientifique et technique (International Office of Epizootics) 27:467-484. Available at: https://www.researchgate.net/publication/23285586_The_impact_of_climate_change_on_the_parasites_and_infectious_diseases_of_aquatic_animals.

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

*Mote P.W., and E.J. Salathé Jr. 2010. Future climate in the Pacific Northwest. Climate Change 102:29–50.

*Mote, P.W., A. F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2008. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86:39-49.

*Oregon Department of Fish and Wildlife (ODFW). 2011. Fish Propagation Annual Report for 2010. Salem, Oregon. 153 pp.

Peterson, W.T., C.A. Morgan, J.P. Fisher, and E. Casillas. 2010. Ocean distribution and habitat associations of yearling coho (*Oncorhynchus kisutch*) and Chinook (*O. tshawytscha*) salmon in the northern California Current. Fisheries Oceanography 19:508-525.

*Piper, R.G., I.B. McElwain, L.E. Orme, J.P. McCraren, L.G. Fowler, and J.R. Leonard. 1982. Fish Hatchery Management. U.S. Fish and Wildlife Service, Washington, D.C.

Reed, T.E., D.E. Schindler, M.J. Hague, D.A. Patterson, E. Meir, R.S. Waples, and S.G. Hinch. 2011. Time to evolve? Potential evolutionary responses of Fraser River sockeye salmon to climate change and effects on persistence. PLoS One 6(6): e20380.

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

Schindler, D.E., X. Augerot, E. Fleishman, N.J. Mantua, B. Riddell, M. Ruckelshaus, J. Seeb, and M. Webster. 2008. Climate change, ecosystem impacts, and management for Pacific salmon. Fisheries 33:502-506.

The White House Council on Environmental Quality (WHCEQ). 2010. Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Change Adaptation Strategy. 53 pp.

Upper Columbia River Salmon Recovery Board (UCSRB). 2007. Upper Columbia Spring Chinook Salmon and Steelhead Recovery Plan. 306 pp.

*U.S. Fish and Wildlife Service (USFWS). 2009. Pacific Region: Fisheries Program Strategic Plan, 2009-2013. U.S. Fish and Wildlife Service, Portland, Oregon.

*U.S. Fish and Wildlife Service (USFWS). 2010a. Rising to the Urgent Challenge: Strategic Plan for Responding to Accelerating Climate Change. 34 pp.

*U.S. Fish and Wildlife Service (USFWS). 2010b. Climate Change Action Priorities for Fiscal Years 2010-2011. 12 pp.

*U.S. Fish and Wildlife Service (USFWS). 2010c. Appendix: 5-Year Action Plan for Implementing the Climate Change Strategic Plan. 22 pp.

*U.S. Fish and Wildlife Service (USFWS). 2013a. Winthrop National Fish Hatchery: Climate Change Vulnerability Assessment, Final Report, December 2013. Climate Change Vulnerability Assessment Team for National Fish Hatcheries, Pacific Region, U.S. Fish and Wildlife Service, Portland, Oregon. 34 pp. + 6 Appendices

U.S. Fish and Wildlife Service (USFWS). 2013b. Review of U.S. Fish and Wildlife Service Hatcheries in Washington, Oregon, and Idaho: Region-Wide issues, Guidelines and Recommendations. Hatchery Review Team, Pacific Region. U.S. Fish and Wildlife Service, Portland, Oregon. 44 pp. Available at: http://www.fws.gov/Pacific/fisheries/Hatcheryreview/reports.html .

*U.S. Fish and Wildlife Service (USFWS). 2016. Quilcene National Fish Hatchery: Climate Change Vulnerability Assessment, Final Report, December 2016. Climate Change Vulnerability Assessment Team for National Fish Hatcheries, Pacific Region, U.S. Fish and Wildlife Service, Portland, Oregon. 49 pp. + 3 appendices.

*U.S. Fish and Wildlife Service (USFWS). 2019. Makah National Fish Hatchery: Climate Change Vulnerability Assessment, Final Report, July 2019. Climate Change Vulnerability Assessment Team for National Fish Hatcheries, Columbia-Pacific Northwest Region, U.S. Fish and Wildlife Service, Portland, Oregon. 44 pp. + 6 appendices.

*U.S. Fish and Wildlife Service (USFWS). 2021a. Warm Springs National Fish Hatchery: Climate Change Vulnerability Assessment, Final Report, August 2021. Climate Change Vulnerability Assessment Team for National Fish Hatcheries, Columbia-Pacific Northwest Region, U.S. Fish and Wildlife Service, Portland, Oregon. 43 pages + 6 Appendices.

*U.S. Fish and Wildlife Service (USFWS). 2021b. Entiat National Fish Hatchery: Climate Change Vulnerability Assessment, Final Report, December 2021. Climate Change Vulnerability

Assessment Team for National Fish Hatcheries, Columbia-Pacific Northwest Region, U.S. Fish and Wildlife Service, Portland, Oregon. 43 pages + 6 Appendices.

Wedemeyer, G.A. 1970. The role of stress in the disease resistance of fishes. Pages 30-35 in: Snieszko, S.F. (editor), A Symposium on Diseases of Fish and Shellfishes. AFS Special Publication No. 5, American Fisheries Society, Bethesda, Maryland.

Wedemeyer, G.A. 1996. Physiology of Fish in Intensive Culture Systems. Chapman and Hall, New York.

*Wedemeyer, G.A. (editor). 2001. Fish Hatchery Management, second edition. American Fisheries Society, Bethesda, Maryland.

Wiens, J.A., and D. Bachelet. 2010. Matching the multiple scales of conservation with the multiple scales of climate change. Conservation Biology 24:51-62.

*Yakama Nation. 2017. Mid-Columbia Coho Restoration Master Plan. Prepared by Yakama Nation Fisheries Resource Management for the Northwest Power and Conservation Council, February 2017. Available at: https://yakamafish-nsn.gov/restore/projects/mid-columbia-coho.

## XIV. APPENDICES

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

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

C. Appendix C. Pathogens and Diseases of Spring Chinook Salmon at Leavenworth National Fish Hatchery.

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

E. Appendix E. Personal Accounts of Previous Floods at Leavenworth NFH

F. Appendix F. Biological and Environmental Uncertainties.