U.S. Fish and Wildlife Service

Columbia-Pacific Northwest Region

Makah National Fish Hatchery

Climate Change Vulnerability Assessment

Final Report: July 2019[1]

U.S. Fish and Wildlife Service

Columbia-Pacific Northwest Region

Climate Change Vulnerability Assessment Team

[1] Revised January 2022.

Please cite as:

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. 45 pp + 6 Appendices.

ACKNOWLEDGEMENTS

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

The following individuals from the Service's Hatchery Evaluation Team (HET) for the Makah National Fish Hatchery (NFH) assisted with the preparation of this report: Benjamin Gilles (Manager, Makah NFH), Jeremy Trimpey (Assistant Manager, Makah NFH), Sonia Mumford (Pacific Region Fish Health Program, Lacey, Washington), Denise Hawkins (Puget Sound, Olympic Peninsula Complex, Lacey, WA), and Pat DeHaan (Western Washington Fish and Wildlife Conservation Office, Lacey, WA).

The following representatives of the Makah Tribe contributed to the adaptive capacity section of this report (Appendix E): Jim Bertolini[2], Mike Chang, Ray Colby, Deb Cooke, Rosina DePoe, Seraphina Gagnon, Joseph Hinton, John J. Ides Sr., Haley Kennard, Bill Mahone Sr., Stephanie Martin, Angela McMurphy, Leah Neuneker, Tiffany Petersen, and Katie Wrubel.

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

[2] Northwest Indian Fisheries Commission (NWIFC).

TABLE OF CONTENTS

I. SUMMARY

Purpose and need

The Fish and Aquatic Conservation (FAC) Program of the Pacific Region of the U.S. Fish and Wildlife Service (Service) is addressing future environmental risks associated with climate change by conducting an extensive evaluation of the vulnerability of its National Fish Hatcheries (NFHs). The NFH Climate Change Assessment Team (Assessment Team), with input from many employees of the FAC Program, initiated quantitative assessments of climate change vulnerabilities in 2011 with a pilot facility, Winthrop NFH (USFWS 2013a), followed by a second pilot assessment for Quilcene NFH (USFWS 2016). The Assessment Team is focused explicitly on NFH vulnerabilities at the local hatchery and watershed levels. Although other agencies are evaluating climate change vulnerabilities in other geographic areas that influence the viability of anadromous salmonid fishes (e.g., freshwater migration corridors and the marine environment), no other entity is evaluating the vulnerability of Service facilities and programs to projected changes in climate.

This series of reports represents the Service's attempt to use the best available science to prepare for future climate conditions and environmental events that could pose a risk to the infrastructure and/or programs at our NFHs. These reports and their underlying analyses are motivated by long-term trends in climate and the increased likelihood of extreme weather events that could significantly affect Service programs and hatcheries in the Pacific Region. The report presented here represents the Assessment Team's Climate Change Vulnerability Assessment for Makah NFH in northwest Washington State.

Definitions

The ***vulnerability*** of a species or system to an *environmental disturbance* such as climate change is a function of four components: sensitivity, exposure, impact, and adaptive capacity.

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

Background and methods

Makah NFH is located at river mile 3.0 on the Tsoo-Yess (formerly Sooes) River in the northwest corner of Washington State near Cape Flattery. The hatchery propagates three species of anadromous salmonid fishes: fall-run Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), and steelhead (*O. mykiss*).

The vulnerability assessment described here was based on climate projections for the 2040s and information provided by the NFH staff and the Service's Hatchery Evaluation Team (HET).[3] Climate projections for the 2040s were derived from downscaled temperature, precipitation, and hydrologic projections in the Tsoo-Yess River basin based on an ensemble of 10 *General Circulation Models* (GCMs)[4], the *A1B emission scenario* (IPCC 2007; UW-CIG[5]), and the *Variable Infiltration Capacity* (VIC) hydrologic model of Liang et al. 1994 (Mantua et al. 2010).

We used those climate and hydrology projections, empirical data on recent fish culture conditions at Makah NFH, and the fish growth model of Iwama and Tautz (1981) to predict future mean size and total biomass of each species (Chinook salmon, coho salmon, steelhead) by month and at each life history stage during the freshwater phase (Appendix B). We then modeled water flow and fish density indexes based on in-hatchery environmental conditions predicted for the 2040s and used associated changes in water temperature and availability as a basis for assessing the impacts of projected climate change to each of the three species propagated at Makah NFH. Based on the results of our analyses, we then used expert opinions from the HET, NFH staff, and the Makah Tribe to evaluate potential adaptive strategies and vulnerabilities of Makah NFH to climate change (Appendix E).

Sensitivity of Makah NFH

Untreated water pumped from the Tsoo-Yess River, primarily a rain-driven watershed[6], is the only source of water for fish culture at Makah NFH. The hatchery has historically contended with low base flows in the Tsoo-Yess River during summer months. As a result, Makah NFH is very sensitive to low surface flows and high water temperatures during the summer, particularly for culturing juvenile coho salmon and steelhead.

The use of untreated surface water from the Tsoo-Yess River exposes all fish at Makah NFH to very high disease risks that are particularly acute during the summer when elevated water temperatures compromise fish immune function and approach the optimum growth temperatures for several important fish pathogens. This sensitivity is exacerbated by the need to partially reuse surface water during the summer, further reducing water quality and increasing disease risks.

Makah NFH is sensitive to flood risks in the late fall and winter from large storms because the watershed has been heavily logged in past years and is a rain-driven watershed. Makah NFH is

---

[3] The Hatchery Evaluation Team consists of the hatchery manager and other technical staff of the Service 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/.

[6] *Rain-driven watersheds* are those where winter precipitation falls primarily as rain (liquid water), whereas *snow-driven watersheds* are those where winter precipitation falls primarily as snow (frozen water). Peak flows of rivers and tributaries in rain-driven watersheds typically occur in late fall and winter, whereas peak flows of rivers and tributaries in snow-driven watersheds typically occur in late winter and spring.

located 20 feet above mean sea level in a tsunami evacuation zone and is also sensitive to localized flooding and saltwater intrusion from storm surges.

Exposure of Makah NFH to climate change

A detailed description of the methods we used to quantitatively assess the *exposure* of Makah NFH to future climates is described in Appendix B.

Surface water temperatures of the Tsoo-Yess River are expected to be warmer in all months, with projected increases in mean monthly temperature ranging from 1.0° C (January) to 2.4° C (July – September) compared to historical averages.

Total annual precipitation in the 2040s is projected to be largely unchanged from historic values but with slightly less precipitation in summer and early fall (May – September) and more precipitation in other months.

Mean annual flows for the Tsoo-Yess River are projected in the 2040s to be slightly greater than the historical mean value, but mean monthly flows are projected to increase by an average of 7.2% in the late fall and winter (October – March) and decrease by an average of 19.1% in summer (June – September).

Projected changes in precipitation and hydrology suggest an increased probability of severe summer droughts and large increases in the magnitude of 100-year winter floods.

Tectonic uplift in the northwest region of the Olympic Peninsula is projected to exceed sea level rise (SLR) through the 2040s. Consequently, flooding of Makah NFH due to SLR is not expected to occur prior to 2050. However, increased intensity of winter storms is expected to increase the probability of localized flooding and saltwater intrusion from storm surges.

Impact of climate change to Makah NFH

Projected future temperatures and water availability on a monthly basis were compared to the published, biological requirements of Chinook salmon, coho salmon, and steelhead to assess the *impacts* of future climate on the propagation programs for those species at Makah NFH (Appendix B).

Higher water temperatures in the 2040s will, most likely, not exceed upper thermal tolerances of Chinook salmon that would preclude continued propagation of the species at Makah NFH; however, higher water temperatures at several life history stages are expected to exceed various physiological thresholds and contribute to a stressful thermal environment. For example, mean water temperatures projected for September will exceed optimal temperatures for holding and spawning adults, and higher water temperatures in the spring will increase disease risks to age 0+ smolts prior to release. In addition, reduced water flows projected in September and early October for the Tsoo-Yess River in the 2040s would most likely impede collection of broodstock during that period.

Projected water temperatures in September and October in the 2040s exceed the optimal spawning temperatures for Chinook and coho salmon. In addition, higher water temperatures during that period are likely to approach the upper physiological limits (12.4° C) for incubation of Chinook salmon eggs.

Higher water temperatures projected for the 2040s from June through September exceed the optimal physiological temperatures for juvenile steelhead and coho salmon.

Higher water temperatures in the 2040s during the spring and summer are expected to approach optimal growth temperatures for several salmonid pathogens, thus increasing disease risks to juvenile steelhead and coho salmon.

Faster growth rates and increased mean sizes of juvenile steelhead and coho salmon throughout their rearing cycles will result in flow and density index values that will approach or exceed culture guidelines for both species in several months under current culture protocols. Higher flow and density indexes projected for the 2040s, particularly during the summer of the first rearing year and in the spring prior to release, are expected to further increase disease risks.

Faster growth rates may also increase the frequency of sexually-mature age 2 males (aka "jacks") among adults for all three species.

Projected increases in precipitation in the fall and winter in the 2040s, falling mostly as rain within the Tsoo-Yess River watershed, are expected to increase the likelihood and severity of floods (e.g., 100-year floods).

Impacts to the infrastructure and fish culture programs of Makah NFH from storm surges and saltwater intrusion are difficult to predict, although disease risks are expected to increase from possible intrusion of saltwater pathogens (*Vibrio* sp.).

Adaptive capacity of Makah NFH

A Workgroup composed of the Assessment Team, the Hatchery Evaluation Team (HET) for Makah NFH, and experts from the Makah Tribe met on January 18, 2018 in Neah Bay, Washington to (a) assess the ability of the hatchery to maintain its current culture programs in face of the expected impacts of projected future climates, and (b) propose adaptation strategies as possible options to reduce those impacts (Appendix E). [Note: Subsequent to the drafting of the report presented here, several of the adaptive measures identified in this report were initiated as pilot studies to evaluate their feasibilities at Makah NFH. Some of the adaptation strategies identified at the January 18, 2018 meeting – and reported here - have been determined subsequently to be logistically (or otherwise) unsuccessful or would require substantial infrastructure changes and annual maintenance for which no current funding exists. For adaptation actions assessed or implemented subsequent to the January 18 meeting, footnotes have been added indicating current assessment status.]

For Chinook salmon, the projected effects of climate change will primarily affect broodstock collection and spawning in the fall, incubation of fertilized eggs, and fish health of age 0+

juveniles in the spring prior to release. Adaptive measures include (1) potential use of seines or traps in the lower Tsoo-Yess River to facilitate broodstock collection in the fall, (2) the use of recirculated, chilled, and disinfected water for holding adult broodstock prior to spawning,[7] (3) the use of chilled water for incubating fertilized eggs in the hatchery building, and (4) early release of age 0+ fish in the spring before rising water temperatures increase disease risks.[8]

Climate change impacts to coho salmon and steelhead are similar; thus, adaptive measures for each species are not independent. These measures include: (1) outplanting of age 0+ coho salmon into the upper Tsoo-Yess River in the spring of their first year - rather than direct release from the hatchery as age 1+ smolts in the spring of their second year - to reduce disease risks (to coho salmon) and water demands at the hatchery during the summer months,[9] (2) installation of a recirculating aquaculture system (RAS) with chilling and disinfection,[10] or (3) discontinuation of the coho salmon program and/or steelhead program, coupled with increasing the size of the Chinook salmon program and/or developing a chum salmon program. An additional possible strategy for steelhead is replacing the existing non-native stock at Makah NFH with an indigenous steelhead stock derived from the existing naturally-spawning population in the Tsoo-Yess River.[11]

The cost of installing a RAS as an adaptive strategy at Makah NFH has been estimated at $4.2 – $6.2 million (2017 dollars; Cutting and Whitbeck 2017). To protect such an investment and to reduce higher flood risks in the 2040s, some members of the Workgroup suggested that relocation of the hatchery farther upstream on the Tsoo-Yess River should be considered as part of implementing the RAS option. Relocation of the hatchery farther upstream would also reduce risks associated with storm surges and saltwater intrusion.

Vulnerability of Makah NFH

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

---

[7] Adaptive measure #2 for Chinook salmon would require the construction of a recirculating aquaculture system (RAS) at Makah NFH. The RAS feasibility assessment report, completed in 2017, estimated a construction cost potentially greater than $6 million and an annual operating cost of nearly $80,000 (Cutting and Whitbeck 2017). The development of a RAS would benefit coho salmon and steelhead also.

[8] Adaptive measure #4 for Chinook salmon (early release of age 0+ subyearlings) is already implemented when necessary.

[9] Adaptive measure #1 for coho salmon was initiated in the spring of 2018 when all brood year (BY) 2017 fish were outplanted in the Tsoo-Yess River as age 0+ subyearlings. Similarly, all BY 2018 coho salmon were also outplanted as age 0+ subyearlings in the spring of 2019. USFWS staff are monitoring and evaluating the potential success of that outplanting strategy.

[10] See footnote #5 above.

[11] A pilot program was initiated in 2018 to assess the ability to capture and spawn natural-origin adult steelhead in the Tsoo-Yess River and then rear their progeny at Makah NFH. USFWS staff are currently monitoring and evaluating the ability to successfully implement this adaptive measure.

Chinook salmon at Makah NFH are considered moderately vulnerable to the projected effects of climate change. Uncertainties exist regarding the future ability to capture adult broodstock in the fall and maintain those adults successfully on station prior to spawning.

Coho salmon and steelhead at Makah NFH are both highly vulnerable to the projected effects of climate change, primarily during the summer months when age 0+ fish are maintained. Adaptive measures for coho salmon and steelhead will, most likely, require major changes in current culture paradigms and/or infrastructure if the propagation of either species is to continue into the 2040s. Steelhead are considered less vulnerable than coho salmon at Makah NFH because (a) adult steelhead return when surface water (from the Tsoo-Yess River) is more abundant and cooler (late fall through spring) than when adult coho salmon return (early fall) and (b) the additional possibility of replacing the existing non-native stock of steelhead with fish derived from the existing naturally spawning population in the Tsoo-Yess River. Several biological or logistic uncertainties are associated with the adaptive measures identified for each species.

The vulnerability of the existing infrastructure at Makah NFH to flooding is expected to increase through the 2040s (and beyond) unless adaptive measures are implemented that will reduce those risks. A high amount of uncertainty exists regarding the ability to protect the existing infrastructure from higher flood risks, including uncertainties regarding the ability to potentially relocate the hatchery farther upstream where flood risks might be lower.

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, particularly the impacts of those effects on smolt-to-adult survivals and return rates, 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 Pacific Northwest to propagate Pacific salmon and steelhead through the 21st Century.

Conclusions

1. The projected effects of climate change will likely not preclude the continued propagation of Chinook salmon at Makah NFH through the 2040s. However, thermal stresses and disease risks are expected to increase, and adaptive measures may need to be implemented.
2. The coho salmon program at Makah NFH is highly vulnerable to the projected effects of climate change and will most likely be unable to continue in the foreseeable future under current culture paradigms. Consequently, significant adaptive measures will need to be implemented if coho salmon are to be propagated at Makah NFH.
3. The steelhead program at Makah NFH - like the coho salmon program - will most likely not be able to continue in the foreseeable future under current culture paradigms. However, adaptive measures implemented for coho salmon – including possible

discontinuation of the coho salmon program – would most likely benefit the steelhead program.

4. Although not explicitly evaluated here in the context of the vulnerability assessment, chum salmon would likely be a viable species for potential propagation at Makah NFH because of their very short freshwater life history.
5. Projected increases in precipitation in the fall and winter in the 2040s are expected to increase the likelihood and severity of floods (e.g., 100-year floods) at Makah NFH.

Recommendations

1. Develop a short-term *adaptation plan* for Makah NFH outlining measures that can be implemented within the next 5 – 10 years.
2. Evaluate the efficacy of using adult traps, seines or trammel nets in the lower Tsoo-Yess River as a future contingency option for collecting adult Chinook salmon for broodstock during low flow periods when surface water is insufficient for attracting adult fish into the hatchery.
3. Estimate the cost and logistics of installing chillers in the hatchery building for incubating fertilized eggs of Chinook salmon.
4. Conduct a preliminary engineering survey and prepare a prospectus for constructing a system for recirculating, chilling, and disinfecting the water used to hold adult broodstock at Makah NFH during the late summer and early fall.
5. Develop a study plan and subsequently evaluate the efficacy of outplanting age 0+ coho salmon in the upper Tsoo-Yess River as an adaptive measure at Makah NFH. The primary goal of the study is to determine whether juvenile survival and adult return rates of outplanted age 0+ coho salmon would be sufficient to (a) maintain a self-sustaining, hatchery-propagated population at Makah NFH and (b) whether such a population, if sustainable, could support an adequate Tribal harvest. [Note: This recommendation was initiated in 2018.]
6. Conduct a "pilot" hatchery program with the indigenous population of steelhead derived from natural-origin adult fish in the Tsoo-Yess River. [Note: This recommendation was initiated in 2018.]
7. Conduct a "pilot" hatchery program for chum salmon at Makah NFH, including a robust monitoring and evaluation effort.
8. Conduct a land survey for possible sites for relocating the fish culture facilities at Makah NFH to an upstream site with lower flood risks in the Tsoo-Yess River watershed.

II. INTRODUCTION

The U.S. Fish and Wildlife Service (Service) in the Pacific Region operates 14 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 2009a). 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 given, until recently, to the evaluation of how future trends in climate will affect hatchery operations in the Pacific Northwest (Hanson and Ostrand 2011). Increased 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 Service has charted a course for 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 2010b, c). One of the Service's priorities is the development of *climate change vulnerability assessments* for species and habitats under federal jurisdiction, National Wildlife Refuges, and National Fish Hatcheries.

In 2011, all National Fish Hatcheries (NFHs) in the United States underwent *qualitative*, climate change vulnerability assessments based on a standardized, spreadsheet template (Appendix A). Although *qualitative* assessments were completed, the Service has identified *quantitative* scientific assessments of the vulnerability of NFHs to climate change as a priority (USFWS 2010a, b). The Pacific Region of the Service 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 14 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 a second pilot assessment at Quilcene NFH on the east side of the Olympic Peninsula (USFWS 2016). These quantitative vulnerability assessments represent the

Service's application of the best available science to prepare for future climate conditions that could pose a risk to the infrastructure and/or programs of our 14 NFHs within the Pacific Region.

The report presented here describes the results of the Service's *quantitative*, climate change vulnerability assessment for Makah NFH and the three species propagated there: Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), and steelhead (*O. mykiss*). Makah NFH is located at river mile 3.0 on the Tsoo-Yess River (formerly Sooes) in the northwest corner of Washington State near Cape Flattery.

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 normal. 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. As a consequence, drought-like summer 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.[12] 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 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).

[12] 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.

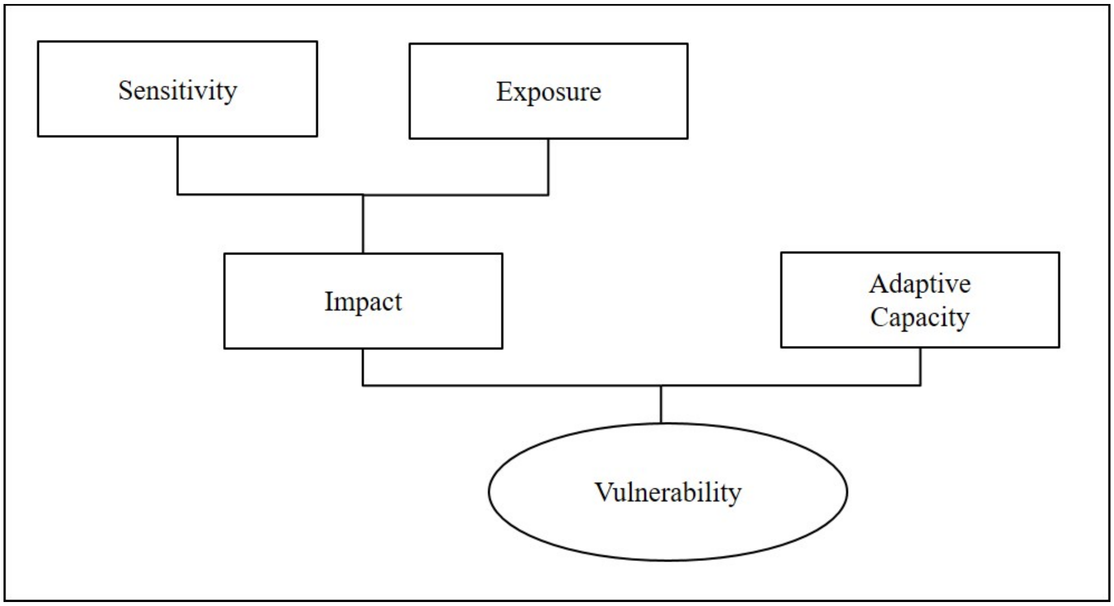

Figure 1. Key components of a vulnerability assessment.

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 summer-flow conditions. We assess sensitivity here in terms of (a) future stressors to the water supply and infrastructure at Makah NFH and (b) the current biomass capacity and productivity limitations of rearing Chinook salmon, coho salmon, and steelhead to the smolt age of development at Makah 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 Tsoo-Yess River basin and the Makah NFH based on statistically-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 Chinook salmon, coho salmon, and steelhead programs at Makah 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 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 might be useful to mitigate for the future effects of climate change; however, additional work is needed to assess the practicality and 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 Chinook salmon, coho salmon, and steelhead programs at Makah 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 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 Environmental Assessment Team (Assessment Team) was created to develop a process for assessing the possible future impacts of climate change on Pacific Region NFH facilities and programs. This process, as described here, (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 GCMs are first downscaled to the river basin of interest. Biotic and abiotic hatchery data are integrated into an analytical framework that allows consistent and transparent evaluations of the effects of projected climate change on NFHs within the specific river basin of interest (Appendix B).

2. The second element combines mathematical modeling of fish growth – based on climate change projections, watershed-specific hydrologic data, and species-specific biological parameters – with *sensitivities* and operational information at the local hatchery level to assess *exposure* and future *impacts* of climate change to specific facilities and fish culture programs (Appendices B, C, D).
3. In the final step of the assessment process, a team of experts - including NFH staff and the HET - work collaboratively with relevant co-managers, stakeholders, and partners to integrate projected impacts of climate change with operational details about the infrastructure and programs at a particular hatchery. The team of experts determines which impacts will likely impede the ability of a hatchery and its programs to meet their goals and then identifies possible adaptive measures. Ultimately, impacts for which there is little or no adaptive capacity are vulnerabilities for the NFH (Appendix E).

IV. BACKGROUND

A. Tsoo-Yess (formerly Sooes) River watershed

Makah NFH is located at river mile 3.0 on the Tsoo-Yess River, eight miles southwest of the town of Neah Bay, Washington, on the northwest tip of the Olympic Peninsula (Figure 2). The river originates in the foothills of the northwest slope of the Olympic Mountains. The mainstem river is approximately 16 miles long with approximately 39 stream miles of tributaries. Except for the headwaters, the Tsoo-Yess River gradient is less than 1% throughout its course.

A waterfall impassible to upstream-migrating salmonids exists at river mile (RM) 13.8. In addition, salmon and steelhead are believed to use only 14 of 39 miles of tributaries for spawning and freshwater rearing. No other physical barriers to fish migration are known except when the hatchery weir is operating. Thermal and low-water flow barriers exist early in the adult migration season for salmon (August through early September) but dissipate with the onset of fall rains, typically in late September.

The Tsoo-Yess River watershed is intensively managed for timber harvest. Major logging occurred during the 1970s, and most stands are less than 35 years old. Habitat quality of the Tsoo-Yess River and its tributaries is generally considered “poor”. Large woody debris is uncommon, and natural recruitment potential for woody debris is currently low because of past logging practices in riparian areas. Nevertheless, spawning gravels and riffles are abundant and are interspersed with resting pools.

Observations made during a site visit by Service staff to the Tsoo-Yess River watershed in October 2000 indicated a dynamic, mobile gravel bed with substantial bar development in some

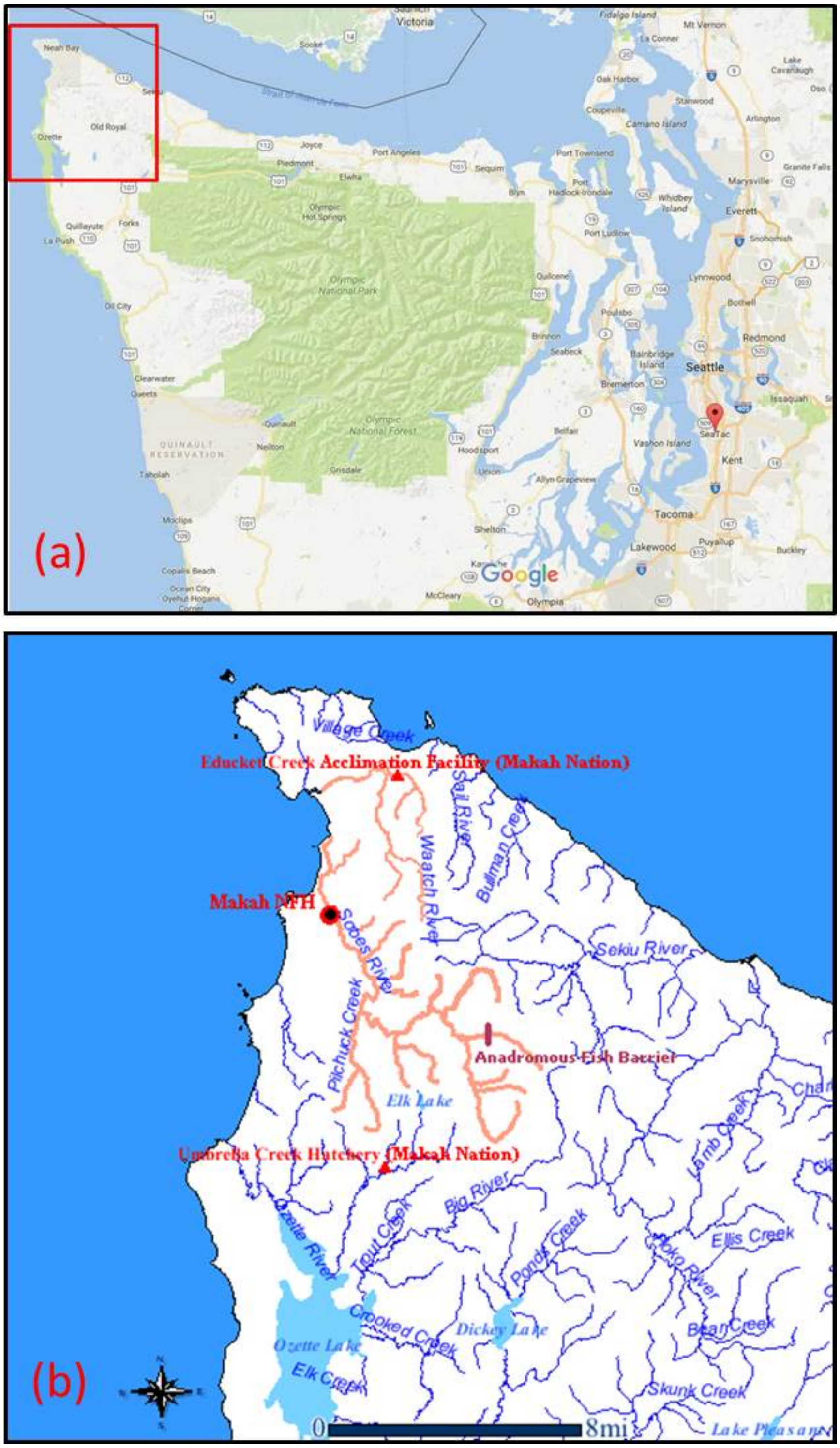

Figure 2. (a) Location of the Tsoo-Yess (formerly Sooes) River watershed (inset) on the northwest tip of the Olympic Peninsula. (b) Location of the Makah National Fish Hatchery (arrow) within the Tsoo-Yess River watershed (in orange). The Makah Tribe also operates an acclimation and smolt release facility on Educket Creek (also in orange). (Modified from https://www.streamnet.org/home/data-maps/).

reaches (Paul Bakke, USFWS, pers. comm., 2000). The gravel composition of the streambed is generally easy for spawning fish to excavate and provides ample intra-gravel water flow. However, the substrate is also easily mobilized during high stream flows. The Tsoo-Yess River experiences a "flashy" hydrologic pattern characteristic of logged watersheds, thus resulting in high sediment transport capacity over brief, but frequent, floods. Mass wasting is also evident in some parts of the watershed that results in substantial movement of fine and coarse sediments to downstream areas.

B. Makah NFH infrastructure

The Makah NFH began operations in 1981 to restore and enhance depleted runs of salmon and steelhead on the Makah Reservation in support of Tribal and other fisheries. The hatchery is situated on approximately 80 acres that are leased by the Service from the Makah Tribe along the west shore of the Tsoo-Yess River. Major physical facilities are described in Appendix C.

C. Water resources at Makah NFH

Tsoo-Yess River

The Tsoo-Yess River provides the only water for fish culture at Makah NFH. This water is neither pathogen-free nor treated to remove/kill pathogens. All water collected from the Tsoo-Yess River passes through a 3/16-inch stainless steel mesh screen and into a water chamber underneath the pump house. Water is pumped from the pump house to a pre-settling pond. This 80,000 square foot pre-settling pond acts as a settling basin to remove suspended solids prior to hatchery use. From that point, water is gravity fed for many fish culture uses at the hatchery. When eggs and fry are present in the hatchery building and incubation/isolation facility, water is pumped through five sand filters (in parallel), each containing 44.2 sq. ft. of filter media and rated at 663 gallons per minute (gpm). When water levels in the river drop during the summer months, a water reuse channel can be utilized. This system allows discharged water from raceways to pass through the abatement system, mix with incoming river water, and be used again in the hatchery.

Water temperatures of the Tsoo-Yess River at the hatchery generally average from 5.5° C (42° F) in January to more than 18.3° C (65° F) in August with peak temperatures approaching 21° C (70° F) during the summer. Through 2000, Tribal staff believed that water temperatures had generally been showing a general cooling trend because of improving canopy cover and riparian conditions (Mike Haggerty, Makah Tribe, pers. comm., 2000). However, the water temperatures during the last three summers (2016 – 2018) have been the highest on record. Summer low flows of the Tsoo-Yess River are typically about 9 cubic feet per second (cfs) at the hatchery.

Ground water

Makah NFH has one well that is used exclusively for the domestic water supply for the residences and hatchery. No wells or other sources of ground water are available currently for fish culture that depends exclusively on untreated surface water from the Tsoo-Yess River.

Water rights

Table 1. Water rights appurtenant to the Makah NFH and temperature range of sources.[13]

Source	Purpose of Use	Lease Start Date	Lease End Date	Amount	Temperature Range
Tsoo-Yess River	Fish culture: raceways, hatchery building	April 15, 2000	April 15, 2025	50 cfs	1.4 – 20.8^{o} C (35 – 70^{o} F)
Groundwater Well 1	Domestic water	N/A	N/A	N/A	N/A

D. Chinook salmon program

Makah NFH propagates Chinook salmon (*Oncorhynchus tshawytscha*) for harvest in tribal, commercial, and sport fisheries. The release goal of 2.3 million smolts (2.2 million at the hatchery + 100,000 smolts into the Wa´atch River) requires 605 pairs of successfully spawned adults annually.

Work completed in the 1990's on the Tsoo-Yess River upstream of the hatchery indicated sufficient spawning habitat is present to support 250 breeding pairs of Chinook salmon. As a consequence, the hatchery has a goal of passing 250 pairs of adult Chinook salmon upstream of the hatchery (3 pairs passed upstream for every 7 pairs retained for broodstock) for natural reproduction, thus yielding a total escapement goal back to the hatchery of 855 adult pairs (1,710 adults total). Management priority has been to complete the hatchery brood requirements before fish are passed upriver. In many years (some sequential), no fish, inadequate numbers of fish, or only males have been available to pass upstream. Chinook salmon typically begin entering the Tsoo-Yess River in August, although adults have been observed as early as mid-July. Poor

[13] The following waters rights/terms at Makah NFH were provided by Jeremy Trimpey, Assistant Manager (June 19, 2017): 9. TERM - The Lessor does hereby lease unto the Lessee, its successors and assigns certain water rights, here in after described, and the aforementioned described land for a term of 25 years, beginning on the l5th day of April 2000 and ending on the l5th day of April 2025. Provided further, the Lessee shall serve the Lessor with notice by mail not less than twelve (12) months prior to the date of expiration of this lease of the Lessee's intent to negotiate a renewal. 18. NONCONSUPTIVE WATER RIGHTS - The Lessee shall have the right to use for fish culture and domestic purposes about 50 cfs water from Sooes River. It is understood that this use is a non-consumptive use. It is further agreed and understood that the Lessees all have the right to construct and maintain necessary ditches, diversions, structures, pipelines, and other facilities which may be required to convey the waters to the leased land over and across lands of the Lessor.

returns of adult Chinook salmon (generally around 1%), low flows, and high water temperatures in the Tsoo-Yess River have been a significant impediment to meeting broodstock collection goals.

Spawning of Chinook salmon at Makah NFH generally occurs from the last week of September through late October, with the adult run ending by mid-November. Chinook salmon eggs are enumerated at the eyed stage (~550 temperature units, TUs) and re-loaded into the incubators at 6,000 eggs per tray.

The earliest progeny lots are typically ponded to the raceways (approximately 240,000 fry/raceway) after yolk sac absorption (1662 – 1690 TUs) around January 20, although this date can vary widely with variable water temperatures. Adipose fin marking and tagging of juveniles typically occurs around March with a coded-wire tag (CWT) target of 200,000 juveniles prior to release. Marked/tagged juveniles are re-ponded at approximately 120,000 fish per raceway. Release of Chinook salmon smolts typically occurs around June 1; however, rising water temperatures and associated disease risks may necessitate an earlier release.

E. Coho salmon program[14]

The release goal for coho salmon (*O. kisutch*) at Makah NFH is 200,000 smolts (+40,000 smolts released into the Wa´atch River) with a broodstock goal of 200 pairs of successfully spawned adults. This adult goal yields more fertilized eggs than necessary for the program but is implemented with the goal of maintaining genetic variation by culling of surplus eggs within families. Work in the 1990's upstream of the hatchery indicated sufficient spawning habitat to support 800 breeding pairs of coho salmon. Consequently, the hatchery has a goal of passing 805 adult pairs upstream of the hatchery for natural reproduction, thus yielding a total escapement goal back to the hatchery of 1,005 adult pairs. Two-year old males (aka "jacks") are scheduled to compose 20% of the spawned males to ensure adequate gene flow among the brood lines spawning every three years.

The genetic lineage of coho salmon propagated at Makah NFH is derived from the population at Quinault NFH. Fish from Quinault NFH were used to initiate the coho salmon program at Makah NFH in 1980 when the hatchery became operational. In 1988, a viral pathogen causing Viral Hemorrhagic Septicemia (VHS) was detected at the hatchery, and all fish on station were euthanized, including efforts to eliminate natural-origin out-migrating smolts that year. The coho salmon program at Makah NFH was restarted with eggs and fry from Quinault NFH.

---

[14] This section describes the age 1+ smolt-release program for coho salmon that was implemented since inception of the program in 1980 through 2018 (BY2016). Beginning with BY2017, all coho salmon were outplanted in the Tsoo-Yess River as age 0+ subyearlings in the spring of their first year (spring of 2018 and 2019 for BY2017 and BY2018, respectively) as an adaptive measure to reduce disease risks and water demands at Makah NFH during the summer months. This adaptive measure is outlined later in the report presented here. Juvenile coho salmon are not reared currently at Makah NFH during the summer (beginning in 2018).

Coho salmon typically begin to enter the lower Tsoo-Yess River in September. Adult return rates have generally met or exceeded broodstock and escapement goals. The coho salmon run to the Tsoo-Yess River is quite protracted (September through early January) with run-time overlap with adult Chinook salmon in the fall. Coho salmon are spawned at the hatchery beginning in late-October and concluding approximately the 3rd week of November.

Fertilized eggs are inventoried at the eyed stage (450 TUs) and loaded back into the incubators at 6,000 eggs per tray. Fry are transferred to raceways after yolk sac absorption (1300 – 1320 TUs) and are typically re-ponded from two raceways to four raceways in mid-June. Marking and tagging occurs in conjunction with re-ponding in June if water temperatures are sufficiently cool to allow tagging without causing stress-related mortality. If water temperatures are not sufficiently cool, the fish are only enumerated and re-ponded into four raceways, with adipose fin marking and tagging (CWT) deferred to mid-October. Marked/tagged coho salmon juveniles are generally re-ponded to six raceways at approximately 42,000 fish per raceway at that time. The current target for CWTs is 55,000 juveniles.

Coho salmon have historically been released as yearling (age 1+) smolts during the first week of April. However, beginning with BY 2017, all age 0+ coho salmon fry were outplanted in the Tsoo-Yess River in the spring of their first year as an adaptive strategy in response to decreasing water flows and increasing temperatures of the Tsoo-Yess River during the summer. Staff from Makah NFH and the USFWS Western Washington Fish and Wildlife Conservation Office (Lacey, Washington) will be evaluating adult returns and the overall efficacy of the fry-outplanting strategy beginning in the falls of 2019 and 2020 when age 2 jacks and age 3 adults, respectively (BY 2017), are expected to return.

F. Steelhead program

The release goal for steelhead (*O. mykiss*) at Makah NFH is 158,000 smolts (+22,000 smolts released into the Wa´atch River) with a spawning goal of 100 pairs of successfully spawned adults. No escapement goal exists for hatchery-origin steelhead upstream of the hatchery in the Tsoo-Yess River because these fish represent an introduced stock from the Quinault NFH (Cook Creek stock). A natural (native) population of steelhead spawns in the Tsoo-Yess River. The natural-origin adults begin arriving in March and are temporally separated from the hatchery-propagated population.

Hatchery-origin steelhead normally begin entering the lower Tsoo-Yess in significant numbers in late October, several months prior to the arrival of natural-origin steelhead. Adult return rates have generally met broodstock goals. Steelhead are spawned at the hatchery beginning in early December, and spawning generally concludes before January 1. Hatchery staff attempt to complete spawning as early as possible to maintain genetic segregation from the natural population. The electric weir remains operational until March 1, after which it is deactivated to allow the natural-origin steelhead to migrate upstream for spawning in the Tsoo-Yess River.

After spawning, steelhead eggs are inventoried at the eyed stage (350 TUs) and loaded back into the incubators at 7,000 eggs per tray. Steelhead fry are transferred to indoor nursery tanks after yolk sac absorption (1080 – 1100 TUs) and subsequently moved into four outdoor raceways in April after smolts of the previous brood year are released.

Marking of juvenile steelhead typically occurs concurrently with coho salmon, around mid-October if water temperatures in June were not sufficiently cool to allow for marking. Marked steelhead are generally re-ponded to raceways at approximately 33,000 fish per raceway. Steelhead at Makah NFH are not tagged with CWTs.

Steelhead smolts are generally released in mid-April, approximately two weeks after coho salmon are released. However, in 2015, steelhead were released one month earlier than normal because of warmer-than-normal river temperatures that resulted in faster growth and earlier smoltification.

G. Supplemental programs

Chinook salmon (100,000 smolts), coho salmon (40,000 smolts), and steelhead (22,000 smolts) are transferred to the Makah Tribe's Educket Creek facility for subsequent release into the Wa´atch River if smolt-release objectives for the Tsoo-Yess River will be met. Fertilized eggs (n = 305,000) from threatened Lake Ozette sockeye salmon (*O. nerka*) are incubated to the eyed stage at Makah NFH, otolith marked, and transferred to streamside incubators adjacent to two tributaries to Lake Ozette: Umbrella Creek (122,000 eyed eggs) and Stony Creek (183,000 eyed eggs).

H. Fish culture parameters at Makah NFH

Fish culture guidelines at Makah NFH are summarized in Table 2. Appendix D summarizes the disease history and pathogens of concern at Makah NFH.

Table 2. Fish culture parameters at Makah NFH.

Species	Density Index (Maximum)	Flow Index (Maximum)	Target release size (fish/lb.)	Target release date	Pathogens / Diseases of Concern*
Chinook salmon	0.2	1.0	75.0	Last week of May	Ichthyobodo sp., *A.sal*
Coho Salmon	0.2	1.0	17.5	First week of April	*A.sal*
Steelhead	0.2	1.0	5.5	Mid-April	Ich, BCWD, *A.sal*

* *Ichthyobodo necatrix and I. pyrifornis*: causative agents of the parasitic disease costiasis). *A.sal* (*Aeromonas salmonicida*): causative agent of furunculosis. BCWD: bacterial cold-water disease, caused by *Flavobacterium psychrophilum*. Ich: also known as "white spot disease", caused by the parasite *Ichthyophthirius multifiliis*.

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 for Makah NFH and the three species of fish currently propagated there relative to current culture protocols.

A. High water temperatures and low surface flows in summer

Makah NFH is very sensitive to low surface flows and high water temperatures during the summer, particularly for culturing coho salmon and steelhead which are reared on station for over one year prior to release in April as yearling smolts. The Makah Tribe withdraws water from the Tsoo-Yess River upstream of the hatchery for domestic use on the reservation. This withdrawal represents another demand besides the hatchery for water during the summer. In most years, water restrictions are implemented for residents of the Makah Reservation from April through October.

Mean water temperature of the Tsoo-Yess River at the hatchery in August has averaged 18.1º C (64.5º F) and often exceeds 20.1º C (70º F) during heat waves (Appendix B). These average temperatures in August exceed the upper optimal growth temperature for juvenile coho salmon (17º C) and are at the upper optimal growth temperature for juvenile steelhead (18º C; Table B1). In addition, mean water temperatures in September and October (15.2º C and 11.3º C, respectively) are near, or exceed, the upper physiological optima for spawning of Chinook salmon (12.3º C) and coho salmon (11.7º C) in September and October, respectively. Any increase in mean or peak surface-water temperatures during the summer and fall at Makah NFH is expected to increase physiological stress and disease risks (see below) to juvenile coho salmon and steelhead. Higher water temperatures in the late summer and fall would also increase risks to adult Chinook salmon during broodstock collection and spawning.

Low flows of the Tsoo-Yess River during the summer, particularly in drought years, have forced partial reuse of surface water for culture. Reuse of water has been achieved by pumping hatchery effluent into a serpentine channel upstream of the facility (Figure 3). This effluent is then mixed with fresh surface water from the Tsoo-Yess River and re-supplied to raceways. As this water passes through each raceway and is then pumped back into the serpentine channel, water quality is reduced by oxygen use and metabolic waste accumulation. This reduced water quality increases the *functional* density and flow indices for fish in raceways above the measured, calculated values. Moreover, because the Tsoo-Yess River and serpentine channel are not pathogen-free, water reuse during periods of insufficient surface flows further increases disease risks.

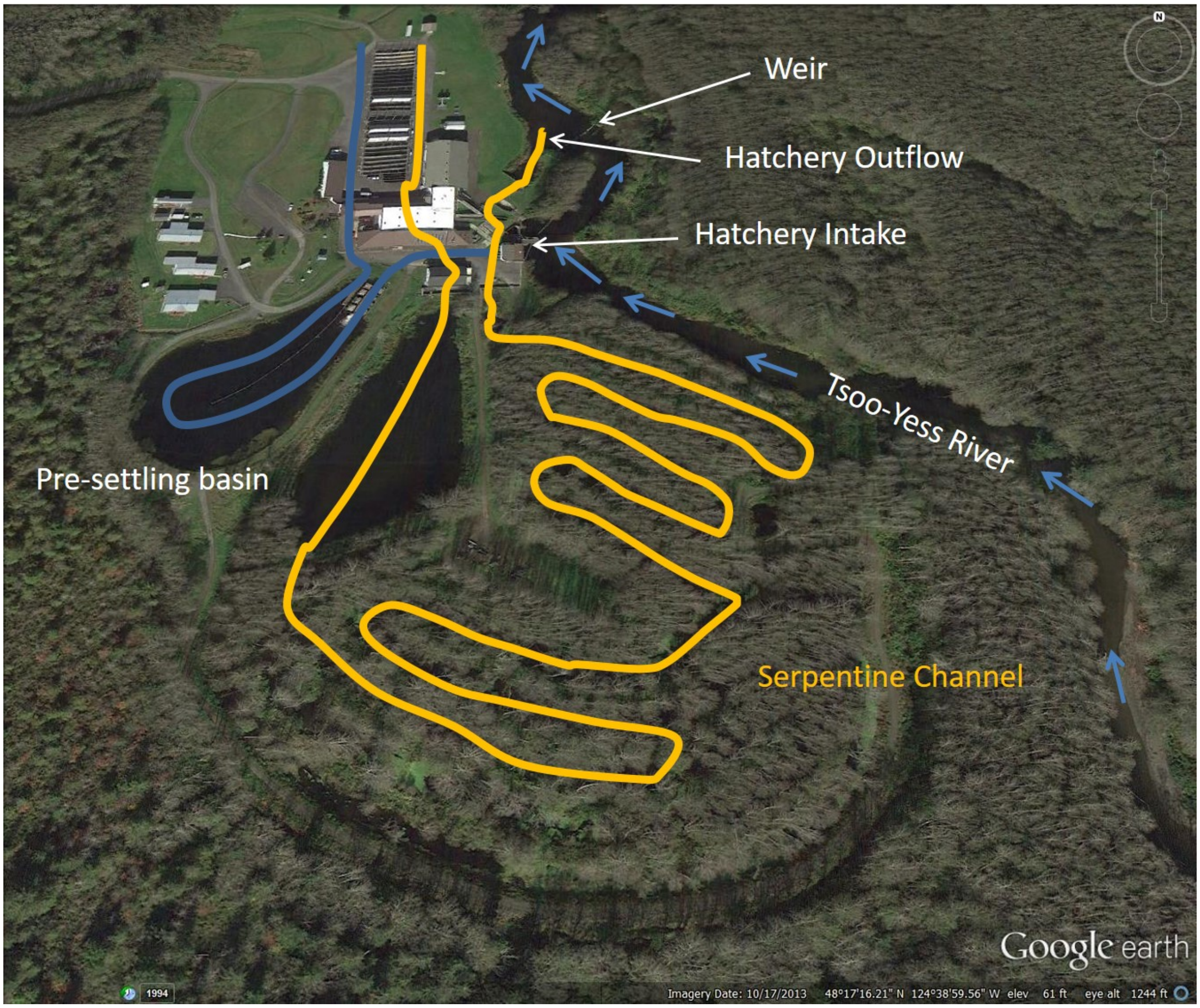

Figure 3. Location and routing of serpentine channel to which effluent water from raceways is pumped during extremely low flows of the Tsoo-Yess River to provide reuse water (mixed with fresh water from the river) back to the raceways for fish culture.

B. Disease risks[15]

Makah NFH is particularly sensitive to environmental stressors that affect disease risks for salmonid fishes, particularly for species that require on-station culture during the summer months (i.e., coho salmon and steelhead). Pathogen loads in the water supply from the Tsoo-Yess River require high use of chemicals (e.g., formalin) and antibiotics (e.g., Florfenicol) to treat fish, particularly in the late spring and summer when increasing water temperatures exceed disease outbreak temperatures (12 – 15º C) and approach optimum growth temperatures (20 – 22º C) for the pathogens that cause furunculosis and Ich (Table B2). Coho salmon are particularly vulnerable to furunculosis and are routinely treated with antibiotics, while large quantities of

[15] See Appendix D: Disease History and Pathogen Risks at Makah NFH.

formalin are used currently to treat steelhead for Ich. Any environmental perturbation that increases pathogen loads or temperatures in the water supply, particularly in the late spring and summer, is expected to further increase disease risks and the likelihood of mortalities among steelhead and/or coho salmon juveniles at Makah NFH. Steelhead at Makah NFH are also susceptible to BCWD (bacterial cold-water disease), particularly when they are transferred from the nursery building to outdoor raceways.

Although Chinook salmon are reared on station for only a few months and are released as age 0+ fish, pathogen loads in the spring associated with rising water temperatures have often required treatment with formalin and/or release of juvenile fish at smaller sizes and at earlier dates than the target sizes and dates, respectively, to reduce disease risks. Any environmental perturbation that increases water temperatures and/or pathogen loads in the early spring would further increase disease risks and affect release schedules for Chinook salmon at Makah NFH.

C. High surface flows and flood risks in late fall and winter

Significant portions of the Tsoo-Yess river watershed have been logged. This relatively low-elevation watershed is primarily "rain-driven" as opposed to "snow-driven". Hence, water flows of the Tsoo-Yess River can increase rapidly during major winter storms and "atmospheric river" events when virtually all the precipitation falls as rain within the watershed. Indeed, the Tsoo-Yess River is characterized as "flashy" because of the rate at which water flows can increase rapidly, and subsequently decrease, in response to storms and runoff. The volume of water carried by winter storms, and the likelihood of atmospheric river events, are positively correlated with local air temperature and mean atmospheric temperatures over the North Pacific Ocean. Hence, Makah NFH is considered sensitive to future floods in response to any future change in atmospheric conditions that increases mean air temperature and the volume of water carried by storms.

D. Storm surges and tsunami risks

Makah NFH is located only three miles upstream from the Pacific Ocean in a tsunami evacuation zone. The hatchery is only 20 feet above mean sea level and is sensitive to flooding and seawater intrusion from storm surges and the potentially catastrophic effects of tsunamis.

E. Sensitivity main points:

- Makah NFH is very sensitive to low surface flows and high water temperatures during the summer, particularly for culturing coho salmon and steelhead. This sensitivity is exacerbated by the need to partially reuse surface water during the summer, further reducing water quality and increasing disease risks.
- Fish at Makah NFH are sensitive to disease, particularly in the late spring and summer.

- Makah NFH is sensitive to flood risks in the late fall and winter from large storms because the watershed has been heavily logged in past years and is a rain-driven watershed.
- Makah NFH is sensitive to localized flooding and saltwater intrusion from storm surges.

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.

A detailed description of the methods we used to quantitatively assess the future exposure of Makah NFH to climate change is described in Appendix B. A summary of those methods is presented below.

A. Methods

To derive predictions of the future climate at Makah NFH in the 2040s, outputs from 10 statistically downscaled GCM simulations for the A1B emissions scenario were used to generate air temperatures in the local watershed. Air temperatures were then converted to surface water temperatures in the Tsoo-Yess River – the only water source for fish culture at Makah NFH – through a series of regression models. The projected surface water temperatures in the 2040s were then compared to baseline water temperatures measured at the NFH's surface intake locations from 1982 – 1989 (Table B3, Appendix B).

To generate estimates for water availability at Makah NFH under the A1B emissions scenario, we used simulated streamflow data from the *Variable Infiltration Capacity* (VIC) hydrologic model (Liang et al. 1994) which was forced by output from the same 10 GCM ensemble used to derive water temperatures (e.g., Mantua et al. 2010). Flow data were summarized as mean monthly surface water discharge in the Tsoo-Yess River routed to the location of Makah NFH (A. Hamlet, Climate Impacts Group, University of Washington, unpublished data).

The impact of sea level rise (SLR) was not explicitly modeled for this report because detailed projections for the area adjacent to Makah NFH are not currently available; however, the rate of SLR has been estimated for other locations nearby (e.g., Neah Bay and Puget Sound). Rates of local SLR similar to those projected by Mote et al. (2008) have been noted for Washington and Oregon (NRC 2012). Those analyses indicated that the downscaled SLR estimates for Neah Bay in 2050 would provide the best surrogate estimate for SLR at Makah NFH. Full SLR modeling details can be found in Mote et al. (2008).

B. Results and Discussion

Climate and hydrologic modeling under the A1B emissions scenario indicate that the Tsoo-Yess River basin will most likely experience warmer air temperatures, higher stream temperatures, lower baseflows in summer, and more extreme winter floods by the 2040s (Tables B3-B5, Figures B1 – B8; Appendix B).

Temperature projections

Mean monthly air temperatures over the entire watershed are expected to increase every month by an average of 1.7º C (S.D. = 0.38º C) by the 2040s, with the largest absolute increases predicted for July through September (2.2 – 2.4º C; Table B4). Similarly, mean surface water temperatures of the Tsoo-Yess River are projected to increase every month with a minimum increase of 1.0° C in January and a maximum increase of 2.4° C in July, August, and September when compared to the historical baseline averages for the 1982 – 1989 period (Table B3; Figure B2).

Precipitation projections

Total annual precipitation is projected in the 2040's to be within 5% of the historical baseline value (256mm vs. 243 mm for projected vs. historic values, respectively) with slightly less precipitation in summer and early fall (12 – 18 mm/mo. decrease, June – September) and more precipitation (10 – 58 mm/mo. increase) in other months (Table B4). The Tsoo-Yess River has a rain-driven hydrology, and modeled projections indicate little change in the overall snow water equivalent (Table B4). There was an indication of reduced future snowpack in January, but the historical estimate is already quite small (Table B4).

Hydrology projections

Based on the VIC hydrologic modeling, mean annual flows projected for the Tsoo-Yess River in the 2040s will be slightly greater than the modeled-historic, annual mean value (485 cfs vs. 454 cfs for projected vs. historic values, respectively; Table B5; Figures B3 – B4). Monthly mean flows are projected to increase in winter by the 2040's, but the magnitude of those flows showed greater uncertainty than the modeled historical values. Mean flows by the 2040s were projected to increase by an average of 7.2% (ensemble range 5.7% to 23.8%) in the late fall and winter (October – March) and decrease by an average of 19.1% (ensemble range -6.0% to -34.6%) in summer (June – September) (Figures B3 and B8). The shape of the hydrographs are generally similar for both historical and 2040s time periods (Figure B3), but the timing of the center in flow mass is projected to be earlier in the year (Figure B5). Projected changes in precipitation and hydrology suggest an increased probability of severe summer droughts (Figure B6) and large increases in the magnitude of 100-year winter floods (Figure B7).

Sea-level rise (SLR) projections

Based on the predictions from Huppert et al. (2009), SLR across a range of scenarios is expected to have limited or no impact on operations at Makah NFH before the 2040s (Appendix B). Only under the 'very high' global SLR scenario would the northwest Olympic Peninsula experience significant SLR (35 cm; Huppert et al. 2009). In this geographic area, SLR is offset by vertical land uplift that is driven by the Juan de Fuca oceanic plate subducting under the North American continental plate (Mote et al. 2008). Although general flooding of the local area around Makah NFH by rising sea level may not be likely by the 2040s, local flooding during storm surges, seawater intrusion into freshwater aquifers, altered ecological conditions in the nearshore riparian zone, and changes in the shape of the freshwater lens from the Tsoo-Yess River may all occur as a result of local SLR (Huppert et al. 2009).

C. Exposure main points:

- Surface water temperatures of the Tsoo-Yess River are expected to be warmer in all months, with projected increases in mean monthly temperature ranging from 1.0° C (January) to 2.4° C (July – September) compared to historical averages.
- Total annual precipitation in the 2040s is projected to be largely unchanged from historic values but with slightly less precipitation in summer and early fall (May – September) and more precipitation in other months.
- Mean annual flows for the Tsoo-Yess River are projected in the 2040s to be slightly greater than the historical mean value, but mean monthly flows are projected to increase by an average of 7.2% in the late fall and winter (October – March) and decrease by an average of 19.1% in summer (June – September).
- Projected changes in precipitation and hydrology suggest an increased probability of severe summer droughts and large increases in the magnitude of 100-year winter floods.
- Sea level rise is expected to have little or no direct impact on Makah NFH by the 2040s, but local flooding due to storm surges, saltwater intrusion into freshwater aquifers, and altered riparian habitats in the lower Tsoo-Yess River could result from rising sea levels.

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 vulnerability of Makah NFH to climate change projections, we first addressed the following question: Could the Chinook salmon, coho salmon, and steelhead programs at the hatchery continue to operate successfully according to the current fish-culture paradigms, following existing schedules and targets, under the climatic conditions projected for the 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 any of the three species, and (b) identify the magnitude and timing of sub-lethal effects (altered growth rates, disease risks, etc.) that may affect survival and growth of each of the three species currently propagated at Makah NFH. Details of our analyses are presented in Appendix B. Those methods are summarized below.

A. Methods

To achieve the foregoing objectives, we (a) collated physiological tolerance data for Chinook salmon, coho salmon, and steelhead, and thermal growth data for common salmon pathogens (Tables B1and B2), (b) adapted a temperature-driven growth model to predict fish growth under projected future conditions in the 2040's, and (c) used flow index and density index parameters (Piper et al. 1982, Wedemeyer 2001) to develop a modeling framework that integrated the future effects of changing temperature and water availability at the Makah NFH (Appendix B). We used the fish growth model of Iwama and Tautz (1981) and empirical data on recent rearing conditions at Makah NFH to predict future mean size and total biomass of each species (Chinook salmon, coho salmon, steelhead) by month at each life history stage during the freshwater phase. We then modeled flow and density indexes based on in-hatchery environmental conditions predicted for the 2040s and used associated changes in water temperature and availability as a basis for assessing the impacts of projected climate change to Chinook salmon, coho salmon and steelhead at Makah NFH.

B. Results and Discussion

Chinook salmon program

Adult Chinook salmon returning to Makah NFH are typically captured for broodstock between September and November and are retained in holding ponds supplied with water from the Tsoo-Yess River until they are spawned. The mean monthly water temperature in the hatchery during the broodstock holding time period is predicted to peak at 17.6° C in September (Table B6; Figure B9) which would exceed the optimal spawning temperatures for Chinook salmon (9.0 – 12.3° C; Table B1). As a result, adult Chinook will likely experience increased physiological stress during holding and spawning in both September and October relative to historic conditions, especially for fish captured and spawned earlier in the run. Those conditions could lead to higher disease risks, pre-spawning mortality, and lower egg quality. In addition, reduced water flows projected in September and early October for the Tsoo-Yess River in the 2040s would most likely impede collection of broodstock during that period because relatively large amounts of water are required to attract adult Chinook salmon into the ladder leading to the adult holding pond at the hatchery.

Higher water temperatures projected for the 2040s (Table B6) are likely to approach the upper physiological limits for fertilized eggs (12.4º C) in the fall and juvenile fish (17.2º C) in the spring prior to release (Table B1; Figure B10). Mean water temperatures in June (17.7° C, Table B3) are projected to exceed the upper limit for proper smoltification (14.0° C, Table B1).

Higher water temperatures at the hatchery during the spring months will likely approach the optimal growth temperatures for several salmon pathogens (Table B2), thereby increasing disease risks. Chinook salmon reared at Makah NFH have been affected historically by pathogens in May prior to release (e.g., *Ichthyobodo* sp. and *A.sal*).

Warmer water temperatures are expected to also increase the mean growth rate of juvenile Chinook salmon (Table B7, Figure B11).[16] The largest increases in mean fish size are predicted to occur in May (warmest month) prior to release when mean fish weight is predicted to increase by 29.3% and mean fish length is predicted to increase by 8.9% compared to historic values (Table B7, Figure B11). Predicted increases in growth rates and mean size will result in small-to-modest increases in flow index values for juvenile Chinook salmon during January – April (Table B8, Figure B12a), but a large increase in flow index is predicted in May when the bias-adjusted value is projected to approach the upper guideline value of 1.0 (Figure B12a). Density index values are also expected to increase with the predicted adjusted value for May exceeding the 0.2 upper guideline value (Table B8, Figure B12b).

Overall, warmer water throughout the year coupled with lower water availability in summer may not pose physiological constraints that preclude propagation of Chinook salmon at Makah NFH in the 2040s. However, higher water temperatures in September and October could increase stress of adult fish held for broodstock, with a potential increase in (a) pre-spawning mortality and (b) disease risks to age 0+ pre-smolts prior to release in the spring.

Coho salmon program

Adult coho salmon returning to Makah NFH are typically captured for broodstock between September and November and retained in holding ponds supplied with water from the Tsoo-Yess River until they are spawned. Water temperatures in September and October in the 2040s are projected to exceed the optimal spawning temperatures for coho salmon (5.7 – 11.7° C; Table B1); hence, it is likely that adult coho salmon will experience increased physiological stress and potential pre-spawning mortality during holding and spawning.

Projected mean temperatures from July through September (17.6 – 20.5° C) in the 2040s exceed the physiological optimal temperatures for juvenile coho salmon (Table B1). By the following April, however, water temperatures at Makah NFH (11.4° C) are not expected to exceed the upper temperature limit for proper smoltification (14.3° C; Table B1).

Projected increases in mean water temperatures in the 2040s during the summer rearing period of June through September (projected means = 17.6 – 20.5° C) are expected to increase disease risks for many pathogens (Table B2) compared to historic conditions. In the 2000's, coho salmon juveniles were often affected by disease outbreaks of furunculosis when water temperatures at the facility exceeded ~15° C, a period that generally lasted from June to early September. Projected increases in water temperatures in the 2040s suggest that the window for disease outbreaks could expand from May to the end of September.

[16] Warmer water temperatures in the fall are expected to cause earlier hatch dates of eggs which, in turn, would increase mean size of fish on specific calendar dates in the future assuming mean spawn dates would remain unchanged. The effect of water temperature on mean hatch date was not specifically modeled here (Appendix B) but could be an important issue at Makah NFH because eggs are incubated in surface water from the Tsoo-Yess River.

Higher water temperatures in the 2040s will also result in faster growth rates of juvenile coho salmon (Table B10, Figure B15). Increases in mean weight and length are predicted to occur in all months, with mean weight predicted to increase by approximately 40% and mean length predicted to increase by approximately 12% by the time yearling smolts are released in April. Predicted increases in mean size of coho salmon at all ages will result in moderate-to-large increases in flow index values throughout the rearing cycle, with the largest increases occurring in August and September - due in part to reduced water availability - and during the last three months of the rearing cycle (February – April) when bias-adjusted values are predicted to approach or exceed the upper guideline value of 1.0 (Table B11, Figure B16a). Density index values are expected to increase in most months, with predicted adjusted values exceeding the upper guideline value of 0.2 in four months: September and the last three months of the rearing cycle, February – April (Table B11, Figure B16b). Higher flow and density indexes during the summer months and prior to release in the early spring are expected to further increase disease risks under current culture protocols. In addition, faster growth rates are expected to increase the frequency of age 2 males (aka “jacks”) among returning adults.

Overall, warmer water throughout the year, coupled with lower water availability in summer, will result in a higher probability that juvenile coho salmon reared under current practices at Makah NFH will face increased physiological stress and a higher probability of disease or mortality compared to historic and current conditions. In addition, water temperatures in the 2040s are expected to exceed the upper physiological thresholds for holding and spawning of adult coho salmon in September and October. These latter effects will most likely lead to increased stress of adult fish trapped and held for broodstock with a potential increase in pre-spawning mortality.

Steelhead program

Adult steelhead are typically captured for broodstock at Makah NFH between November and January and retained in holding ponds supplied with water from the Tsoo-Yess River until they are spawned. Mean water temperatures during this adult holding period in the 2040s are projected to increase by 1.0° C to 1.3° C (compared to historic values) but would still be within the optimal spawning temperatures for steelhead (6.4 – 15.3° C; Table B1).

Mean water temperatures at Makah NFH from June through September in the 2040s are projected to exceed the optimal physiological temperatures for juvenile steelhead (Table B1). By the following April, however, water temperatures at Makah NFH (11.4° C) are expected to be within the upper temperature limit for proper smoltification (12.6° C; Table B1).

Projected increases in water temperatures in the 2040s during the summer rearing period June through September (projected means = 17.6 – 20.5° C) are expected to increase disease risk (Table B2) compared to historic conditions. In the 2000’s, steelhead juveniles were often afflicted with Ich when water temperatures at the hatchery exceeded ~13° C, a period that historically lasted from June to September. That window for disease outbreaks could extend from May to October in the 2040s.

Higher water temperatures in the 2040s will also result in faster growth rates of juvenile steelhead (Table B13, Figure B19). Increases in mean weight and length are predicted to occur in all months, with mean weight predicted to increase by approximately 42% and mean length predicted to increase by approximately 12% by the time yearling smolts are released in April. Predicted increases in mean size of steelhead at all ages will result in moderate-to-large increases in flow index values throughout the rearing cycle, with the largest increases occurring in August and September - due in part to reduced water availability - when bias-adjusted values are predicted to exceed the upper guideline value of 1.0 (Table B14, Figure B20a). Density index values are expected to increase in all months (Table B14), with predicted bias-adjusted values exceeding the upper guideline value of 0.2 in six of 14 months (Figure B20b). These predicted index values could result in potential culture issues in August and September - before the fish are marked/tagged and re-ponded at lower densities if tagging occurs in October - and during the last four months of the rearing cycle. Higher density indexes during the summer months are also expected to further increase disease risks under current culture protocols. Faster growth rates may also increase the frequency of sexually-mature age 2+ males (aka “jacks”) among returning adults.

Overall, warmer water throughout the year, coupled with lower water availability in summer, will result in a higher probability that juvenile steelhead reared under current practices at Makah NFH will face increased physiological stress, disease, and mortality compared to historic and current conditions. On the other hand, water temperatures in the 2040s during November through January are expected to remain below the upper physiological thresholds for holding and spawning of adult steelhead.

Hatchery infrastructure

Larger floods in the fall and winter projected for the 2040s (Figures B7 and B8) may pose an increased risk of damage to hatchery infrastructure. While Makah NFH is located only 4.8 kilometers (3 miles) upstream of the Pacific Ocean, direct flooding due to projected SLR is not expected to be a major concern for the facility in the 2040’s because of tectonic uplift of the land and continued isostatic rebound from the last glacial epoch. However, increased risk of coastal flooding during winter storm surges could be a concern for the facility and could lead to local flooding of low-lying areas and saltwater intrusion into freshwater aquifers. Reduced summer base-flows of the Tsoo-Yess River in the 2040s would most likely necessitate increased use of reuse water pumped back into the serpentine canal under current culture protocols, thus reducing water quality and further increasing disease risks to steelhead and coho salmon.

C. Impact main points:

- Higher water temperatures in the 2040s will most likely not exceed upper thermal tolerances of Chinook salmon that would preclude continued propagation of the species at Makah NFH; however, higher water temperatures at several life history stages are expected to exceed various physiological thresholds and contribute to a stressful thermal environment. For example, mean water temperatures projected for September will exceed optimal temperatures for holding and spawning adults, and higher water temperatures in the spring will increase disease risks to age 0+ smolts prior to release. In addition, reduced water flows projected in September and early October for the Tsoo-Yess River in the 2040s would most likely impede collection of broodstock during that period.

- Projected water temperatures in September and October in the 2040s exceed the optimal spawning temperatures for Chinook salmon and coho salmon. In addition, higher water temperatures during that period are likely to approach the upper physiological limits (12.4° C) for incubation of Chinook salmon eggs.
- Higher water temperatures projected for the 2040s from June through September will exceed the optimal physiological temperatures for juvenile steelhead and coho salmon.
- Higher water temperatures in the 2040s during the spring and summer are expected to approach optimal growth temperatures for several salmonid pathogens and increase disease risks to juvenile steelhead and coho salmon.
- Faster growth rates and increased mean sizes of juvenile steelhead and coho salmon throughout the rearing cycles of both species will result in flow and density index values that will approach or exceed culture guidelines for both species in several months under current culture protocols. Higher flow and density indexes projected for the 2040s, particularly during the summer of the first rearing year and in the spring prior to release, are expected to further increase disease risks.
- Faster growth rates may also increase the frequency of sexually-mature age 2 males (aka "jacks") among adults for all three species.
- Projected increases in precipitation in the fall and winter in the 2040s, falling mostly as rain within the Tsoo-Yess River watershed, are expected to increase the likelihood and severity of floods (e.g., 100-year floods).
- Sea level rise (SLR) is not expected to directly affect Makah NFH, but localized flooding and saltwater intrusion into freshwater aquifers may occur with increased likelihood from more intense storms and higher storm surges.

VIII. ADAPTIVE CAPACITY

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

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

A. Methods

A Workgroup led by the Assessment Team was formed, composed of the Hatchery Evaluation Team (HET) for Makah NFH and experts from the Makah Tribe. The Workgroup met on January 18, 2018 in Neah Bay, Washington to (a) assess the ability of the hatchery to maintain its current culture programs in face of the future impacts of climate change, and (b) propose possible adaptation strategies to reduce those impacts consistent with the mission and goals of the hatchery and its programs (Appendix E). Members of the HET provided technical expertise and experience to assess the capability of Makah NFH and its programs to adapt to the projected impacts of climate change. Staff from the Makah Tribe provided key insights regarding tribal needs and goals, and they also provided expert technical advice regarding possible adaptation strategies.

The Workgroup identified a limited number of adaptive capacity options (Appendix E). The Makah Tribe emphasized the importance of both coho salmon and steelhead to their cultural needs and fishing subsistence. Tribal representatives also noted that adaptation strategies for Makah NFH could not be addressed in isolation of the water resource needs of the Tribe and other water demands on the Tsoo-Yess River but need to be addressed as part of a holistic ecosystem strategy. Some Workgroup members expressed concern about costly infrastructure investments that might be negated by future climate change. Many of the adaptation strategies identified in the Results section below are currently being implemented.

B. Results and Discussion[17]

Chinook salmon program

1. ***Impact:*** Mean water temperatures of the Tsoo-Yess River projected for the 2040s in September (17.6° C) exceed the optimal spawning temperatures for Chinook salmon (9.0 – 12.3° C). In addition, reduced water flows projected in September and early October could impede collection of broodstock during that period because of insufficient water to attract adult Chinook salmon into the hatchery.

   (a) Infrastructure adaptations: (1) Develop a recirculating water system with chillers and disinfection for the adult holding pond.*[18]

[17] Several of the infrastructure adaptation options outlined in this section, while possible, would require large monetary investments for which funding would need to be identified. These options are indicated by an asterisk (*).

[18] Chinook salmon require a large volume of attraction water to swim up the ladder into the adult holding pond. The Workgroup concluded that it is not feasible at the present time at Makah NFH to chill the large volume of water required for attracting and holding Chinook salmon broodstock, but the water used for holding adult broodstock prior to spawning could be chilled if recirculated (Ben Gilles, Manager, Makah NFH, pers. comm., January 18, 2018).

***(b) Protocol and management adaptations**:* (1) Collect broodstock by seine or traps in the lower Tsoo-Yess River and transport to the adult holding pond at the hatchery, thereby eliminating the need to discharge large quantities of water from the adult holding pond to attract Chinook salmon volitionally for broodstock. (2) Outplant age 0+ coho salmon in the upper Tsoo-Yess River in the spring, thereby allowing more water to be available for attracting and holding adult Chinook salmon in the fall.[19]

2. ***Impact:*** Higher water temperatures projected for the 2040s are likely to approach the upper physiological limits for fertilized eggs (12.4º C) during the egg incubation period.

   (a) Infrastructure adaptations: (1) Chill incubation water in the hatchery building.*

   (b) Protocol and management adaptations: None identified.

3. ***Impact:*** Higher water temperatures projected for the 2040s in May are expected to (a) approach the upper physiological limits for proper smoltification of Chinook salmon, and (b) will likely increase the probability of infectious disease in age 0+ Chinook salmon prior to release.

   (a) Infrastructure adaptations: None identified.

   (b) Protocol and management adaptations: (1) Release juvenile Chinook salmon earlier than current target dates to reduce disease risks (*implemented currently*). (2) Use formalin and antibiotics as needed to prevent and/or treat disease (*implemented currently*).

4. ***Impact:*** Faster growth rates of Chinook salmon juveniles will likely result in density index values in May that exceed the 0.2 guideline, further increasing disease risks.

   (a) Infrastructure adaptations: None identified.

   (b) Protocol and management adaptations: (1) Develop feeding strategies to reduce growth rates. (2) Release juvenile Chinook salmon earlier than current target dates to stay within fish-density guidelines (*implemented currently*).

Coho salmon program

1. ***Impact:*** Mean water temperatures of the Tsoo-Yess River projected for the 2040s in September (17.6º C) and October (13.3º C) exceed the optimal spawning temperatures for coho salmon (5.7 – 11.7° C). As a result, adult coho salmon trapped and held for broodstock will likely experience increased physiological stress during holding and spawning, potentially increasing pre-spawning mortality.

---

[19] Pilot studies to assess the efficacy of outplanting age 0+ coho salmon in the upper Tsoo-Yess River were initiated in 2018.

(a) Infrastructure adaptations: (1) Develop a recirculating water system with chillers and disinfection for the adult holding pond.*

(b) Protocol and management adaptations: (1) Discontinue the existing coho salmon program and consider increasing the size of the fall Chinook salmon program and/or develop a chum salmon program.

2. ***Impact:*** Projected water temperatures from July through September in the 2040s (projected monthly means = 17.6 – 20.5° C) exceed the optimal physiological temperatures for juvenile coho salmon. Higher water temperatures during the late spring and summer, coupled with lower water availability, are expected to increase disease risks to juvenile coho salmon (especially for furunculosis) compared to current and historic conditions.

   (a) Infrastructure adaptations: (1) Install a recirculating water aquaculture system (RAS) and disinfect the source water from the Tsoo-Yess River and during recirculation.*[20]

   (b) Protocol and management adaptations: (1) Use formalin and antibiotics as needed to prevent/treat fungal and bacterial infections, respectively (*implemented currently*). (2) Outplant age 0+ coho fry into the upper Tsoo-Yess River watershed in the spring to reduce disease risks and increase survival potential of coho juveniles. Pilot studies have been initiated to test the efficacy of this latter adaptation strategy. (3) Discontinue the existing coho salmon program and consider increasing the size of the fall Chinook salmon program and/or develop a chum salmon program.

3. ***Impact:*** Faster growth rates of juvenile coho salmon will result in larger mean lengths and weights in most months of the rearing cycle leading to (a) predicted flow index values that approach or exceed the upper guideline value of 1.0 in February – April prior to release and (b) predicted density index values that exceed the upper guideline value of 0.2 in four months (September, and February – April prior to release). Higher density indexes are expected to further increase disease risks under current culture protocols.

   (a) Infrastructure adaptations: None identified.

   (b) Protocol and management adaptations: (1) Develop feeding strategies to reduce growth rates. (2) Suspend feeding when water temperature exceeds 18° C (*implemented*

[20] It would be difficult to disinfect 100% of the source water in the current flow-through aquaculture system, but it would be feasible to disinfect the source water from the Tsoo-Yess River and recirculated water in a RAS (Ben Gilles, Manager, Makah NFH). However, development of a RAS would be a major investment to the hatchery infrastructure ($4.2-$6.2 million in 2017 dollars; Cutting and Whitbeck 2017). As such, to protect such an investment, it may be desirable to simultaneously relocate the fish culture facilities farther upstream on the Tsoo-Yess River where water quality is higher, flood risks are lower, and the threat of saltwater intrusion is removed (see discussion in Appendix E).

currently). (3) Reduce raceway volumes to increase water turnover rates (*implemented currently*).

4. ***Impact:*** Faster growth rates of juvenile coho salmon, including larger mean size of smolts at release, will likely increase the frequency of sexually-mature, two-year old males (aka "jacks") among returning adults.[21]

   (a) Infrastructure adaptations: None identified.

   (b) Protocol and management adaptations: (1) Develop feeding strategies to reduce growth rates.

Steelhead program

1. ***Impact:*** Projected water temperatures from June through September in the 2040s (projected monthly means = 17.6 – 20.5° C) exceed the optimal physiological temperatures for juvenile steelhead. Higher water temperatures during the late spring and summer, coupled with lower water availability, are expected to increase disease risks to juvenile steelhead (especially for Ich and furunculosis) compared to current and historic conditions.

   (a) Infrastructure adaptations: (1) Install a recirculating water aquaculture system (RAS) and disinfect the source water from the Tsoo-Yess River and during recirculation.*

   (b) Protocol and management adaptations: (1) Use formalin and antibiotics as needed to prevent/treat fungal and bacterial infections, respectively (*implemented currently*). (2) Outplant age 0+ coho fry into the upper Tsoo-Yess River watershed in the spring, thereby increasing the amount of water available for steelhead at the hatchery during the summer. (3) Discontinue the existing steelhead program and consider increasing the size of the fall Chinook salmon program and/or develop a chum salmon program.

2. ***Impact:*** Faster growth rates of juvenile steelhead will result in larger mean lengths and weights in all months of the rearing cycle leading to (a) predicted flow index values that exceed the upper guideline value of 1.0 in August and September and (b) predicted density index values that exceed the upper guideline value of 0.2 in six of 14 months (July, August, and January – April prior to release). Higher density indexes during the summer months are expected to further increase disease risks under current culture protocols.

   (a) Infrastructure adaptations: None identified.[22]

---

[21] Ocean conditions will also affect the frequency of sexually-mature coho salmon returning at two years of age.

[22] Water chillers for incubation of Chinook salmon eggs could be used also to delay hatching and emergence of steelhead fry, effectively reducing total biomass during the summer months.

(b) Protocol and management adaptations: (1) Develop feeding strategies to reduce growth rates. (2) Suspend feeding when water temperature exceeds 18° C. (*implemented currently*). (3) Reduce raceway volumes to increase water turnover rates (*implemented currently*). (4) Outplant age 0+ coho fry into the upper Tsoo-Yess River watershed in the spring to increase available water for summer rearing of steelhead at the hatchery. (5) Discontinue the current "non-native" steelhead program and develop a native steelhead program integrated with the naturally spawning population. Implementation of this latter option would reduce water demands for age 0+ steelhead during their first summer because steelhead from the naturally-spawning population in the Tsoo-Yess River return and spawn several months later (April – June) than the current hatchery population (November – December), thus resulting in a substantially smaller amount of total biomass for the same number of age 0+ fish during the summer.

3. ***Impact:*** Faster growth rates of juvenile steelhead, including larger mean size of smolts at release, will most likely increase the frequency of sexually-mature, non-migrant males in the released population.

   (a) Infrastructure adaptations: None identified.

   (b) Protocol and management adaptations: (1) Develop feeding strategies to reduce growth rates. (2) Discontinue the current non-native steelhead program and either (a) replace with a new steelhead program derived from natural-origin adults returning to the Tsoo-Yess River, or (b) consider increasing the size of the fall Chinook program and/or developing a chum salmon program.

Hatchery infrastructure

1. ***Impact:*** Greater precipitation projected in the fall and winter for the Tsoo-Yess River basin in the 2040s is expected to increase flood risks to Makah NFH. The magnitude of 100-year floods is expected to increase by approximately 25% by the 2040s.

   (a) Infrastructure adaptations: Relocate the hatchery to a new location farther upstream in the Tsoo-Yess River watershed.*

   (b) Protocol and management adaptations: None identified.

2. ***Impact:*** Increasing storm intensities in the 2040s, coupled with sea-level rise, are expected to increase the likelihood of localized flooding and saltwater intrusion into the hatchery during storm surges. Saltwater intrusion into the hatchery would also pose a disease risk to fish on stations from *Vibrio* sp., a saltwater pathogen of salmonid fishes.

   (a) Infrastructure adaptations: Relocate the hatchery to a new location farther upstream in the Tsoo-Yess River watershed.*

   (b) Protocol and management adaptations: None identified.

3. ***Impact:*** Reduced water availability from the Tsoo-Yess River projected for the summer months in the 2040s would require more reuse water to be pumped back through the serpentine channel to meet the fish culture needs of coho salmon and steelhead. More reuse water would reduce water quality, increase effective density indexes, and increase disease risks to coho salmon and steelhead.

   (a) Infrastructure adaptations: (1) Disinfect the source water prior to delivery to the hatchery (e.g., ozonation).* (2) Install a recirculating water aquaculture system (RAS), and disinfect the source water from the Tsoo-Yess River and during recirculation.*

   (b) Protocol and management adaptations: Discontinue the coho salmon and/or steelhead programs and consider increasing the size of the fall Chinook program and/or developing a chum salmon program.

Chum salmon

One adaptive measure discussed at the January 18, 2018 Workgroup meeting, and previously by the Service and Makah Tribe, was the potential development of a chum salmon program as a replacement for the coho salmon program and/or steelhead program. Chum salmon fry migrate to saltwater within a couple months after hatching (and absorption of their yolk sac), thus allowing hatchery propagation in locations where freshwater is extremely limited during the late spring through early fall (May – October) but sufficient to support adult migration during the late fall and early winter (November – December).

C. Adaptive Capacity main points (options):[23]

- Collect adult Chinook salmon for broodstock with seines or traps in the lower Tsoo-Yess River, if necessary.
- Chill incubation water for Chinook salmon eggs. Chillers could be used also to delay hatch and emergence of coho and steelhead fry, thereby reducing total biomass demands during the summer.
- Recirculate, disinfect, and chill – as needed – the water used to hold adult Chinook and coho salmon broodstock prior to spawning.*
- Outplant age 0+ coho salmon into the upper Tsoo-Yess watershed to reduce disease risks and water demands for fish culture at the hatchery during the summer months.[24]

---

[23] Infrastructure adaptation options indicated by an asterisk (*) would require large monetary investments for which funding would need to be identified.

[24] A pilot study to assess the feasibility of this option was initiated in 2018. This study will use DNA markers and physical tags to compare the adult-to-smolt productivities, and the smolt-to-adult return rates, of the following three groups of adult coho salmon: (1) adults spawned in the hatchery with rearing of their progeny at the hatchery to the smolt stage prior to release; (2) adults spawned in the hatchery but with their age 0+ progeny outplanted into the upper Tsoo-Yess River, and (3) adults allowed to swim upstream to spawn naturally.

- Replace the existing non-native hatchery stock of steelhead with an indigenous steelhead hatchery stock derived from natural-origin steelhead in the Tsoo-Yess River.
- Discontinue the existing coho salmon program and/or steelhead program and consider increasing the size of the fall Chinook salmon program and/or developing a chum salmon program.
- Relocate the hatchery to an upstream location in the Tsoo-Yess River watershed to reduce flood risks and equip with a recirculating aquaculture system (RAS)*.

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. Chinook salmon

Chinook salmon at Makah NFH are moderately vulnerable to the projected effects of climate change. The primary vulnerabilities are uncertainties regarding the lower flows and higher temperatures projected for the Tsoo-Yess River in the 2040s when adults typically return to the hatchery. A biological assumption, or hypothesis, is that the natural life history of Chinook salmon will adjust to changing river and ocean conditions, assuming that the current population at Makah NFH has the biological resiliency to adapt accordingly.

B. Coho salmon

Coho salmon at Makah NFH are highly vulnerable to the projected effects of climate change. The future ability of the hatchery to maintain age 0+ coho salmon on station throughout the summer months without costly investments in infrastructure is questionable. Uncertainties also exist regarding the feasibility of the proposed adaptive measure to outplant age 0+ fish into the upper watershed rather than rearing those fish at the hatchery to the yearling smolt stage prior to release. For example, the ability to propagate coho salmon at viability levels that can support harvest, or even maintain a self-sustaining hatchery population, when age 0+ fish are outplanted is unknown. Additional uncertainties exist regarding the extent to which lower water flows and higher temperature of the Tsoo-Yess River projected for the 2040s will impede upstream migration of coho salmon to Makah NFH.

C. Steelhead

Steelhead at Makah NFH are highly vulnerable to the projected effects of climate change but not quite as much as coho salmon. In contrast to coho salmon (and Chinook salmon), higher water temperatures are not expected to affect broodstock collection, but disease risks during the late spring and summer are expected to increase. Adaptive measures proposed for coho salmon could reduce those risks by allowing more water available for steelhead – thus lowering density and flow indexes during the critical summer period – but higher water temperatures would still favor pathogens and potential disease outbreaks. Potential use of the native steelhead stock, as opposed to the current non-native stock, is one option that would potentially reduce the vulnerability of a steelhead program at Makah NFH if the juvenile rearing period could be restricted to one year. However, many uncertainties would need to be resolved before this latter adaptive measure could be fully implemented (e.g., ability to capture and successfully spawn broodstock, hatching success of fertilized eggs, etc.).

D. Hatchery infrastructure

The vulnerability of the physical infrastructure of Makah NFH to greater storm intensities in the late fall and winter, including storm surges up the Tsoo-Yess River, is expected to increase by the 2040's. Potential engineering modifications to reduce those vulnerabilities were largely beyond the expertise of the Work Group. Although sea level rise is not considered a vulnerability prior to 2050, it is expected to increase flood risks in the vicinity of the hatchery by the end of the 21st Century.

E. Vulnerability main points:

- Chinook salmon at Makah NFH are moderately vulnerable to the projected effects of climate change.
- Coho salmon at Makah NFH are highly vulnerable to the projected effects of climate change and, most likely, cannot be maintained on station during the summer months in the foreseeable future under current culture paradigms.
- Steelhead at Makah NFH are highly vulnerable to the projected effects of climate change, but to a lesser extent than coho salmon. Adaptive measures implemented for coho salmon could benefit steelhead.
- The projected effects of climate change would likely have little effect on the ability of Makah NFH to propagate chum salmon.
- Makah NFH is vulnerable to higher flood risks due winter storms and storm surges by the 2040s and more so by the year 2100 due to sea level rise.

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, 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 Pacific Northwest to propagate Pacific salmon and steelhead through the 21st Century. Details regarding these uncertainties are described in Appendix F.

XI. CONCLUSIONS

1. The projected effects of climate change will most likely not preclude the continued propagation of Chinook salmon at Makah NFH through the 2040s. However, some adaptive measures may need to be implemented.
2. The coho salmon program at Makah NFH is highly vulnerable to the projected effects of climate change and will most likely be unable to continue in the foreseeable future under current culture paradigms. Consequently, significant adaptive measures will need to be implemented if coho salmon are to be propagated at Makah NFH.
3. The steelhead program at Makah NFH - like the coho salmon program - will most likely not be able to continue in the foreseeable future under current culture paradigms. However, adaptive measures implemented for coho salmon – including possible discontinuation of the coho salmon program – would most likely benefit the steelhead program.
4. Although not explicitly evaluated here in the context of the vulnerability assessment, chum salmon would likely be a viable species for potential propagation at Makah NFH because of their very short freshwater life history.
5. Flood risks to Makah NFH are expected to increase in the foreseeable future due to increased intensity of winter storms and storm surges up the Tsoo-Yess River.

XII. RECOMMENDATIONS

1. Develop a short-term *adaptation plan* for Makah NFH outlining measures that can be implemented within the next 5 – 10 years.
2. Evaluate the efficacy of using adult traps, seines or trammel nets in the lower Tsoo-Yess River as a future contingency option for collecting adult Chinook salmon for broodstock during low flow periods when surface water is insufficient for attracting adult fish into the hatchery.
3. Estimate the cost and logistics of installing chillers in the hatchery building for incubating fertilized eggs of Chinook salmon.
4. Conduct a preliminary engineering survey and prepare a prospectus for constructing a system for recirculating, chilling, and disinfecting the water used to hold adult broodstock at Makah NFH during the late summer and early fall.
5. Develop a study plan and subsequently evaluate the efficacy of outplanting age 0+ coho salmon in the upper Tsoo-Yess River as an adaptive measure at Makah NFH. The primary goal of the study is to determine whether juvenile survival and adult return rates of outplanted age 0+ coho salmon would be sufficient to (a) maintain a self-sustaining,

hatchery-propagated population at Makah NFH and (b) whether such a population, if sustainable, could support an adequate Tribal harvest. [Note: This recommendation was initiated in 2018.]

6. Conduct a "pilot" hatchery program with the indigenous population of steelhead derived from natural-origin adult fish in the Tsoo-Yess River. [Note: This recommendation was initiated in 2018.]
7. Conduct a "pilot" hatchery program for chum salmon at Makah NFH, including a robust monitoring and evaluation effort.
8. Conduct a land survey for possible sites for relocating the fish culture facilities at Makah NFH to an upstream site with lower flood risks in the Tsoo-Yess River watershed.

XIII. REFERENCES[25]

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. Can. J. Fish. Aquat. Sci. 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.

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. 173pp.

*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 (USFWS) Division of Economics. 75 pp.

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

Dawson, T P., S.T. Jackson, et al. 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 .

Halofsky, J.E., D.L. Peterson, K.A. O'Halloran, and C.A. Hoffman (eds.). 2011. Adapting to Climate Change at Olympic National Forest and Olympic National Park. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. 130 p.

[25] Cited references are indicated by an asterisk (*).

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

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

Henderson, J.A., Peter, D.H., Lesher, R.D., Shaw, D.C. 1989. Forested plant associations of the Olympic National Forest. Ecol. Tech. Paper R6-ECOL-TP-001-88. U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Olympic National Forest. Olympia, Washington. 502 p.

*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. 151pp. 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 J. Marine Sci. 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, Maryland.

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.

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

*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.

*National Research Council (NRC). 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. The National Academies Press, National Academies of Science, Washington, D.C. 201 pp. Available at: https://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington .

*Oregon Department of Fish and Wildlife (ODFW). 2011. Fish propagation annual report for 2010. Salem, OR. 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 p.

*U.S. Fish and Wildlife Service (USFWS). 2009a. Pacific Region: Fisheries program strategic plan 2009-2013. U.S. Fish and Wildlife Service, Portland, OR, USA.

U.S. Fish and Wildlife Service (USFWS). 2009b. Makah, Quinault, and Makah National Fish Hatcheries: Assessments and Recommendations. Final Report, May 2009. Hatchery Review Team, Pacific Region. U.S. Fish and Wildlife Service, Portland, Oregon. http://www.fws.gov/pacific/fisheries/Hatcheryreview/ team.html. 263 pp

*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, December 2013. Climate Change Assessment Team for National Fish Hatcheries, Pacific Region. U.S. Fish and Wildlife Service, Portland, Oregon. 34 pp.

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. 44pp. 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 Vulnerabilty Assessment Team for National Fish Hatcheries, Pacific Northwest Region. U.S. Fish and Wildlife Service, Portland, Oregon. 49pp. + 3 appendices.

Wedemeyer, G.A. 1970. The role of stress in the disease resistance of fishes, p. 30-35. In: Snieszko, S.F. (ed.), 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. Reprinted by Springer, USA (https://link.springer.com/book/10.1007%2F978-1-4615-6011-1). 232pp.

*Wedemeyer, G.A., editor. 2001. Fish hatchery management, second edition. American Fisheries Society, Bethesda, MD. 751pp.

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.

XIV. APPENDICES

A. **Appendix A.** Qualitative Assessments of Climate Change Vulnerability of National Fish Hatcheries in the Pacific Region: Makah National Fish Hatchery.

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

C. **Appendix C.** Major Physical Facilities at Makah NFH.

D. **Appendix D.** Disease History and Pathogenic Risks at Makah NFH.

E. **Appendix E.** Work Group Meeting Notes, Neah Bay, Washington, January 18, 2018.

F. **Appendix F.** Biological and Environmental Uncertainties.