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A spatio-temporal assessment of health in Hanford Reach Chinook salmon in relation to contamination incidents from the Hanford Site nuclear complex

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Abstract

A nuclear weapons production plant in Washington state, USA created substantial chemical and toxic waste between the 1940s and 1980s. With radioactive half-lives of up to 4.5 billion years, the waste has not been neutralized or safely stored, some potentially becoming more toxic to the environment as time passes. Laboratory-based estimates of pollution impact were compared with available *in situ* data to evaluate the health of wild Chinook salmon breeding in the river that borders this nuclear facility. Health parameters were assessed for the naturally spawning Hanford Reach population of fall-run Chinook across eight decades. Lab exposure experiments indicate that Hanford Chinook spawning habitat is both diminished and threatened by the contamination plumes. Historic and contemporary monitoring and testing are insufficient, allowing an unknown number of leaks to go undetected into the Chinook spawning grounds. Due to ongoing and poorly documented contamination seepage outflows across the area of study, spanning the past eight decades, it is difficult to establish a baseline for control years. Known and presumed pollution leaks are identified, and compared to Chinook salmon health parameters through time and the geographic area.

Introduction

Between World War II and the Cold War, a nuclear complex in the Pacific Northwest region of the United States created plutonium for more than 60,000 nuclear weapons, including the Trinity bomb and the atomic bomb that devastated Nagasaki, Japan (Gallucci, 2020). In the early 1940s, this area of Washington state was evacuated, relocating farming communities and Native American tribes (United States Department of Energy, 2021) to allow for construction of the nuclear plant along a large, free-flowing section of the Columbia River (Lewis, 2021). That portion of river is called the “Hanford Reach” of the Columbia, and the now-decommissioned nuclear compound is known as the Hanford Site. The Hanford Reach is the largest (Nugent, 2016) and most productive (Richards & Pearsons, 2019) remaining natural spawning ground of Chinook salmon (*Oncorhynchus tshawytscha*) in the world (Northwest Power & Conservation Council, 2021).

Since the Hanford Site’s decommissioning at the end of the Cold War, scientists have spent three decades attempting to decontaminate the 177 tanks of radioactive sludge, and the government is challenged to afford the monumental task of neutralizing the environmental risks they pose.

Commissioned by the US Department of Energy, the largest engineering project in the world is underway to build the Waste Treatment and Immobilization Plant, also known as the Hanford Vit Plant, sprawled across 25 hectares, or 65 acres (Gallucci, 2020), to process and stabilize the 56 million gallons of radioactive and chemical waste currently stored within the Hanford Site (DOE, 2007). Despite the construction already being underway and the US government currently estimating that it will require US $16.8 billion to finish the project, the proper funds to do so are unavailable, and the science to safely and effectively vitrify the toxic waste has not yet been developed (Leckband, 2007) (Martin, 2005) (Hanford Advisory Board, 2012) (DOE, 2019) (Gallucci, 2020). As they wait, the aging, corroding vessels containing 212 million liters of toxic waste — enough to fill 85 Olympic swimming pools (Gallucci, 2020) — are leak-prone single-shell tanks, built between 1943 and 1964. Using the technology available at the time, the tanks were built to last 20 years. At least six have been leaking actively since 2013, and 59 others are assumed to have previously lost waste through leaks and spills (US Department of Energy, 2020). The tanks have been recorded to have leaked roughly 4 million liters of radioactive waste into the Hanford Reach of the Columbia River. 1,800 environmentally unsafe contaminants have been identified inside the tanks, including plutonium, uranium, cesium, aluminum, iodine, and mercury (Gallucci, 2020). The human population surrounding Hanford— known as “down winders”— has statistically higher rates of thyroid disorders, Beryllium Disease (Leckband, 2009), and childhood cancer, as well as increased infant and fetal mortality rates (Cate & Hansom, 1986) linked to the river pollution and proximity to the Hanford Site in a number of court cases. Of the thousands of Hanford workers and residents of “down winder” communities involved in consolidated class action lawsuits, many lost or died while waiting for a verdict, which sometimes took decades to reach. In October 2015, the U.S. Department of Energy [hereafter referred to as DOE] resolved the final cases, paying more than $60 million in legal fees and $7 million in damages to a fraction of the plaintiffs, which in the end was not enough to cover their legal costs from the trial or medical bills. In that same court ruling, similar “down winder” cases from more than 2,300 others were turned away (McClure, 2011) (Boyle, 2017). Displaced Native American communities, who rely on salmon fishing from the Columbia as a cultural way of life, were allowed to move back into the area after the Hanford Site’s [hereafter called the Site] decommissioning. These populations and other “down winders” were exposed disproportionately to leaking Hanford contaminants (Advisory Committee on Human Radiation Experiments, 1995) (Hudson, 2014) (Leckband & Hudson, 2012) before classified details of the Manhattan Project’s effects became available to the public (Washington Office of Superintendent of Public Instruction, 2015). To date, there is no comprehensive review of the Hanford Reach Chinook data in relation to years with known contamination leaks.

The population of fall Chinook that spawns in the Hanford Reach has ecological, cultural, and economic importance that reaches downstream and along the Pacific Ocean from Alaska to California (Dauble & Watson, 1997). The Hanford Reach spawning area and fall Chinook population are classified as Level 5 resources, the “highest ranking, rarest, and most sensitive habitats and species… considered irreplaceable or at risk of extirpation or extinction” (Nugent, 2016) (Dauble & Watson, 1997). This population and their spawning habitat are of significant interest to federal, state, and Tribal governments, as well as the public; as “these fall Chinook salmon have been vital in efforts to preserve and restore other depleted Chinook salmon stocks in the Columbia Basin” (Anglin *et al*., 2006) as far east as Idaho (Nugent, 2016). The detailed status of past, present, and future Hanford Reach Chinooks needs to be monitored (Dauble & Watson, 1990) in relation to Site contaminants, as continually leaking toxic waste could have a major impact on their survival in the Columbia River.

Published studies on Hanford Reach Chinooks, as well as lab-based experiments exposing hatchery Chinooks to controlled amounts of Hanford Site contaminants, indicate potential health and environmental impacts of the contamination leaks on wild Chinook salmon spawning habitat. Existing research shows that Chinooks exposed to Hanford Site contaminants in lab settings experience growth retardation, smaller final body sizes, lower survival rates into adulthood, non-lethal health impairments such as kidney lesions and biochemical changes, as well as behavioral impacts that could be classified as Wildlife Injury under DOI’s NRDA regulations (Hanford Natural Resource Damage Assessment Injury Assessment Plan, 2013).

Salmon spawning areas at Hanford are contaminated by chromium, strontium-90, and uranium, among other radioactive and chemical pollutants (Washington State Department of Ecology, 2020) (Riverkeeper, 2011). This project aimed to compare existing data from known higher and lower contamination years, based on identified major leaks, to assess if wild Hanford Reach Chinooks show similarly fluctuating indicators of population health. Data will include individual parameters such as fecundity rates— to determine if fish hatched in higher radiation years have lower fecundity at spawning— as well as body size, survival rates, and environmental indicators of population health, such as nest counts, and distortions of sex ratios. Additionally, the objective was to assess if results from the lab-based studies exposing Chinooks to precise amounts of Hanford contaminants were an indicator of the health effects recorded in wild fish.

Methods

Within various tributaries of the Columbia River, the numerous populations identified from study areas exhibit vastly different life history traits such as expected body sizes, fecundity, age at spawning, and seasonal migration patterns. Hence, this study focused on a specific Hanford population to compare across eight decades in an attempt to determine the potential impact of contaminant exposures to health of Hanford's fall Chinook population.

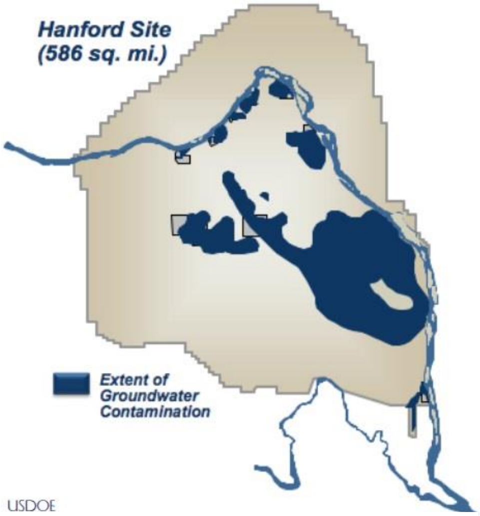
In addition to conducting a literature review, fish data was gathered and analyzed from public government databases, annual fishery reports, published records and studies, and when needed and possible, directly from the original scientists who collected data. The two main federal databases used were the Regional Mark Processing Center (RMPC) and PTAGIS, the comprehensive information system for PIT and coded wire tags in all Columbia River fish. This information was available for public use under the United States' Freedom of Information Act. The data on contamination leaks was sourced from the U.S. Department of Energy (DOE), Pacific Northwest National Laboratory (PNNL), the U.S. Fish & Wildlife Service (USFWS), Mission Support Alliance (MSA), Battelle Memorial Institute, Bonneville Power Administration, Energy Northwest, the Advisory Committee on Human Radiation Experiments (ACHRE), and substantiated private contractor reports. Authenticated documents from court cases and verified tribal reports were also used sparingly.

Gaining an overarching picture of the spatio-temporal landscape in Hanford Chinook health through the literature review, the data analysis set out to further combine multivariate aspects of fish health, habitat health, and contamination presence from manifold sources and decades.

Results

Groundwater and Geography

The most hazardous liquid wastes from the Hanford Site were pumped into underground storage tanks. The remaining waste– an estimated 440 billion gallons of contaminated liquid– was dumped into the soil in unlined ponds, trenches, ditches, and sometimes injected directly into the groundwater. "Leaking storage tanks and unplanned spills added to the contaminated liquids in the soil. As a result, there is extensive contamination of groundwater beneath the Hanford site" (Oregon Department of Energy, 2021). Chemical and radioactive contamination currently affect more than 180 square miles of the Site's groundwater– more than 70 square miles being above the federal regulatory drinking water standards (*Figure 1*) (Oregon Department of Energy, 2021)– in addition to other large areas of the Site where underground tanks, cribs, and burial grounds leak radioactive waste that continues to percolate down into the ground water, some of which will only get worse with time (US Government Accountability Office, 2005) (Reeves, 2007). A 2011 scientific review of the Hanford Site's geography found that the natural down-gradient flow of groundwater from the Site toward the Columbia River provides the conduit for chemical and radioactive contamination to continue (Riverkeeper, 2011). "Groundwater flows toward the Columbia River and is the primary exposure route for contaminants to reach human, environmental, and ecological receptors" with hexavalent chromium the primary concern in the river corridor (Hartman & Ivarson, 2011). Pollution plumes have been recorded migrating down from the surface, reaching the groundwater, and leaching directly into the Columbia River. Contamination also enters the river through groundwater upwellings. Studies showed that contamination from Hanford was still found in river life along the Hanford Reach as of 2011 (Riverkeeper, 2011).



USDOE

Figure 1: Groundwater contaminated above regulatory levels is flowing toward the Columbia River.

Photo and caption information from (Riverkeeper, 2011).

Declining Fish Health

For thousands of years, the Columbia River supported the most abundant salmon runs on Earth which supported a sustainable Native American fishery (National Resource Council, 2004). Despite the Hanford Reach being the largest remaining natural spawning grounds of fall Chinook salmon (Nugent, 2016), the runs today are a fraction of their former magnitude due to loss of habitat, dams, over-harvest, and polluted water. The Hanford Reach is home to forty-three species of fish, and since the late 1990s, the National Marine Fisheries Service has recognized 13 different salmon stocks as threatened and endangered with extinction, requiring protection under the Endangered Species Act. Some of the salmon spawning areas at Hanford are contaminated by chromium, tritium, strontium-90, uranium and other pollutants (*Figure 3*) (Riverkeeper, 2011).

Contaminants

Hanford nuclear reactors produced dozens of hazardous waste products, including radioactive and chemical pollutants. The unknown quantity and distribution of wastes (Martin, 2005) adds to the complexity of the cleanup process, as well as understanding the dangers of the unique toxic mixtures of nuclear waste reactions (Reeves, 1997). The contaminants covered here are strontium-90, hexavalent chromium, tritium, uranium, carbon tetrachloride, iodine-129, and technetium-99; as those exist throughout the Site in significantly higher quantities or pose greater risk to the health of Hanford Reach wildlife than other pollutants not included here. The seven contaminants act as alpha and beta particle radiation emitters (Health Physics Society, 2001) (CDC, 2021) (Cook *et al*., 2003) (U.S. NRC, 2020). Since weapons production and fish experimentation began in 1943, scientific understanding of the effects of these contaminants has changed greatly (Foster, 1971). Effluent from the Hanford reactors contained "virtually every kind of radionuclide likely to be encountered in the liquid wastes of contemporary light water power reactors, but in quantities substantially greater… The releases of radioactive materials from the Hanford plants to the atmosphere and to the Columbia River have been orders of magnitude greater than those that are associated with the normal operation of power reactors of contemporary design" (Foster, 1971). In the early years of Hanford production, "fish and the lower forms of life" were assumed to be "more resistant to radiation than man" (Foster, 1971). In addition to studying the effects of x-rays on fish in the 1940s, the University of Washington exposed Chinooks in an aquatic laboratory to radiation doses 40x the levels measured in the Hanford spawning grounds during that time, which was 1000x greater than would have been naturally present in the river before the Hanford Site was built. Although the number of abnormal fish was markedly increased by the irradiation, "the size and number of fingerlings was not significantly affected" and it was considered "no adverse effect could be seen at that time" so "these young fish were then liberated and left to compete with natural stocks" in the Hanford Reach (Foster, 1971).

Understanding radioactive half-life is integral to assessing that dangers posed to fall Chinook salmon populations and their environment. An isotope's half-life is the amount of time required for half of the nuclei to undergo radioactive decay. For example, strontium-90 is a hazardous waste product currently found in Hanford groundwater along the banks of the river at concentrations several times greater than the drinking water standard (*Figure 2*); however, strontium-90 has a half-life of 29 years, which means that in 29 years it will diminish to half its original quantity through the process of radioactive decay (Centers for Disease Control and Prevention, 2004). "Some of the radionuclides released from Hanford in the past are no longer of concern because of their short half-lives, such as iodine-131, which has a half-life of 8 days. Other radioactive elements are extremely long-lived. The half-life of iodine-129, for example, is over 15 million years, posing a significant long-term threat to the Columbia River" (Riverkeeper, 2011).

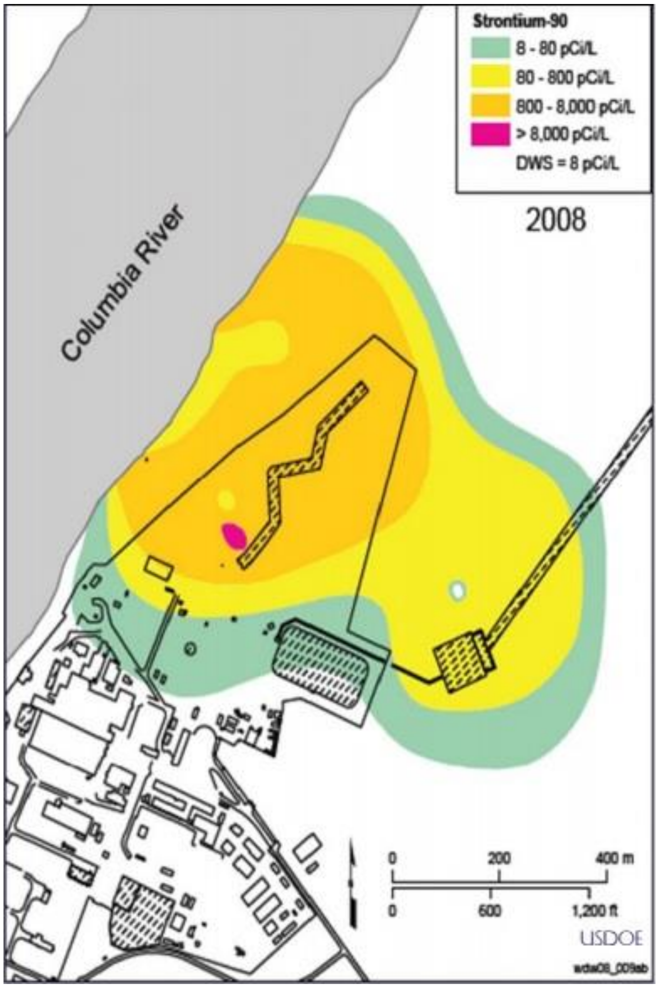


Figure 2: Strontium-90 is a radioactive waste product that causes leukemia, bone, and lung cancers; immune system suppression; and Acute Radiation Syndrome in humans (Centers for Disease Control and Prevention, 2004). During and after Hanford's operative years, the federal government discharged strontium-90 into unlined trenches along the Columbia River. Strontium-90 levels can be seen here in color gradient, with hatched structures overlain to represent the original Hanford Site buildings still present above and below ground (Riverkeeper, 2011).

Plumes of strontium-90 are flowing through the groundwater, directly into the river at concentrations 1000 times greater than safe levels, and have not changed in decades. Despite this documentation, the DOE's 2010 Work Plan recommended no additional sampling of the waste sites to locate the exact source (Virgin, 2010). The Hanford Advisory Board, which will be covered in detail later in this section, identified the DOE's decision not to further sample and pinpoint the source as "questionable" (Leckband, 2010).

Strontium-90 concentrates in fish tissues. Samples at a Savannah River site showed fish tissues concentrating strontium-90 thousands of times above levels in the ambient water (Poston *et al*., 2009). Health effects salmon may experience after bioaccumulating strontium-90 are birth defects, weakened bones, thinning of the skin, lesions, vision loss, and cancer; while humans who consume these animals uptake the long-lived contaminant into their bones much like calcium absorption. Because they are still growing, children and young animals retain a maximum level of Strontium-90 in their gastrointestinal tract and bones. They are especially susceptible to negative health effects as a result, including but not limited to stunted bone growth and lung disease (Centers for Disease Control and Prevention, 2004). This increases the importance of preventing strontium-90 from reaching the Columbia River.

The U.S. Department of Energy is attempting to intercept the plume of strontium with barrier wells near the Columbia River shore, but levels entering the Columbia River still exceed safe levels. The City of Richland's drinking water intake pipe is roughly 30 miles downstream from the riverbank Strontium plume. Current health standards do not account for the potential bioaccumulation of pollutants in the food chain and the above-average rates of fish consumption by some populations, particularly Native Americans. Despite other contaminants such as hexavalent chromium being dangerous to salmon at concentrations (10 µg/L) well below the drinking water standard (100 µg/L), safe strontium-90 levels for fish are unknown and the government assumes the drinking water standard of strontium is protective of aquatic life (Riverkeeper, 2011).

Chromium: During Hanford's operative years, chromium was added to cooling water in the nuclear reactor cores to prevent corrosion. Today, Hanford's nine reactor sites on the banks of the Columbia River are all contaminated with chromium. The hexavalent form of chromium is a human carcinogen and even small amounts are highly toxic to salmon and aquatic life (Poston *et al*., 2009). Chromium plumes along the river and other areas in the central Hanford Site exceed the EPA's drinking water standard for chromium of 100 µg/L (Riverkeeper, 2011). To reduce the chromium to a less harmful form, the DOE has attempted bioremediation of the soil. However, a 2006 U.S. Government Accountability Office report stated that these efforts have not been successful in preventing chromium from entering the Columbia River (Poston *et al*., 2009). According to the EPA, any chromium concentration greater than 10 µg/L is unsafe for salmon. Scientists observed chromium upwelling into the bottom of the Columbia at levels as high as 112 µg/L – exceeding the safe level by more than 1000% (U.S. Government Accountability Office, 2005).

Chromium bioaccumulates in shellfish in the Columbia River near chromium groundwater plumes, and has been proven to harm salmon by impacting fertilization success and reducing growth in juvenile salmon, as well as proving lethal to salmon in high concentrations (Riverkeeper, 2011). A 2018 study in Washington state linked chromium exposure in fish to mucus overproduction, respiratory disturbance, spinal deformities, anemia, neurological damage, and possible growth reduction (Department of Natural Resources and Parks, 2018) (Wood *et al*., 2012). Scientists have discovered groundwater upwelling into Hanford Reach spawning areas that contain hexavalent chromium levels deemed unsafe by the EPA and the State of Washington (U.S. Department of Energy, 2009) (Pacific Northwest National Laboratory, 2007). Spring Chinook spend more time in-river after hatching than fall Chinook, indicating a potentially higher exposure to radioactive and chemical wastes (Woodward *et al*., 1999). Because of chromium's acute toxicity, the DOE established a goal of preventing further chromium contamination into the Columbia River. Continued chromium upwelling into the Columbia River suggests that the Department is not meeting this goal (U.S. Government Accountability Office, 2005) (Riverkeeper, 2011). Exposing threatened and endangered salmon, and the people who eat salmon, to hexavalent chromium is a serious concern (U.S. Department of Energy, 2010) (Hanford Advisory Board, 1997). The Hanford Reach provides irreplaceable spawning habitat for fall and spring Chinook salmon. Continued contamination of these spawning beds may reduce salmon available to downstream fisheries (Riverkeeper, 2011).

Tritium: Tritium is a radioactive isotope of hydrogen often found in water at the Hanford Site that can act as a beta-emitter. High doses can contribute to cancer, lowered reproductive organ function on in both males and females, brain damage, hormone dysregulation, cataracts, and DNA damage in humans, fish, or other species (Canadian Nuclear Safety Commission, 2010) (Riverkeeper, 2011). The federal government caused tritium contamination by discharging huge volumes of polluted cooling water into uncontained ponds and ditches during years of operation. Tritium is present in the Columbia River's Hanford Reach and, like chromium and strontium-90, may pose a risk to near-shore areas of the river and to the aquatic species that use these (Riverkeeper, 2011). The tritium plume at Hanford is currently the most extensive known radionuclide plume on the site (*Figure 3*), with over 49 square miles of Hanford groundwater containing tritium at levels that exceed drinking water standards by a factor of at least 10, and as of 2011 there were no remediation efforts in place (Nuclear Regulatory Commission, 2009) (Hartman & Ivarson, 2011). The highest levels of tritium currently reaching the Columbia River occur in springs and groundwater seepages at the Hanford Town site and the most southern Hanford Reach area near the river, which is within 30 miles of Richland's drinking water supply (Poston *et al.*, 2009). The high concentrations of tritium contamination in these areas are at levels proven to be harmful to both aquatic species and humans in laboratory testing (Canadian Nuclear Safety Commission, 2010) (Riverkeeper, 2011). The plume has already migrated more than 15km toward the river, though the half-life of tritium is 12.3 years (Canadian Nuclear Safety Commission, 2010), which

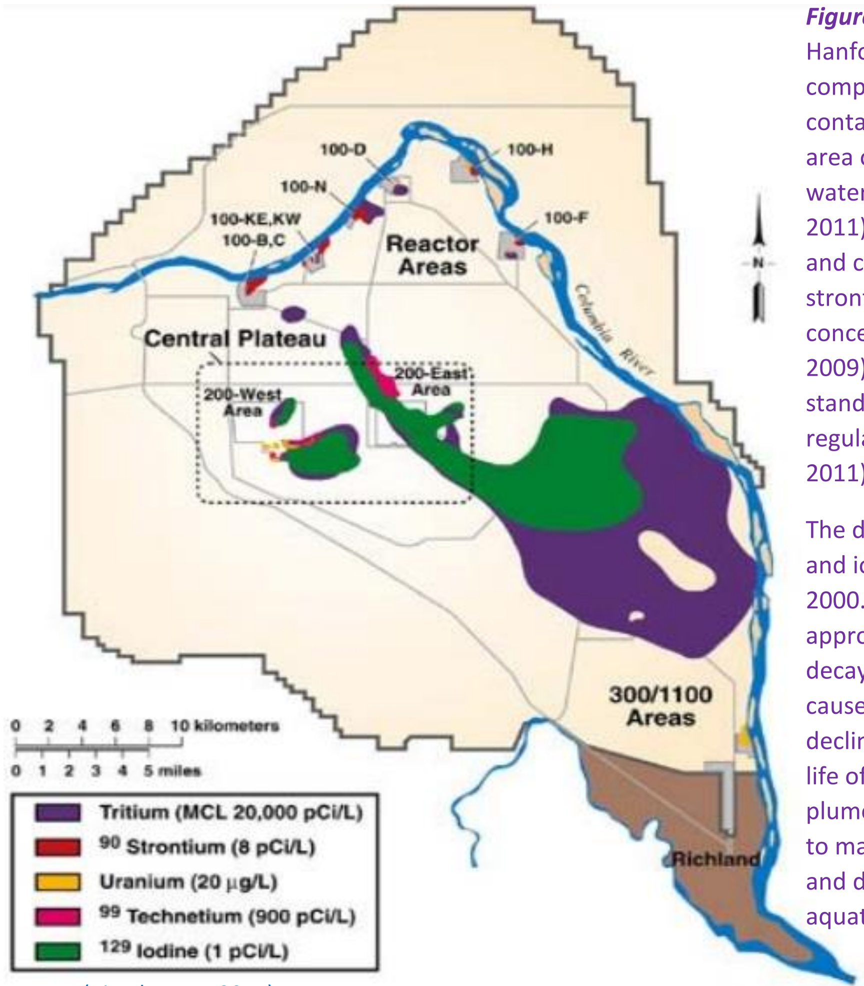


Image: (Riverkeeper, 2011).

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Figure 3: Groundwater plumes at the Hanford Site. Tritium and iodine-129 comprise the most extensive contamination areas, with a combined area of over 72 mi^2 not meeting drinking water standards (Hartman & Ivarson, 2011). Because some of the radioactive and chemical contaminants such as strontium– seen along the river in red– concentrate in fish tissues (Poston *et al.*, 2009), EPA regulations for drinking water standards are often less stringent than regulations for aquatic life (Riverkeeper, 2011).

The dimensions of the Site-wide tritium and iodine-129 plumes have declined since 2000. Tritium has a half-life of approximately 12 years, so radioactive decay and dispersion through the river has caused the tritium concentrations to decline. Iodine-129, however, has a half-life of 17 million years, so its decline in plume size since the year 2000 is expected to mainly be a consequence of advection and dispersion into the surrounding aquatic and atmospheric environment, where it may bioaccumulate in fish (Hartman & Ivarson, 2011).

indicates that the tritium contamination threat is gradually shrinking as concentrations of this isotope decline through radioactive decay, dispersion, and discharge to the Pacific Ocean via the Columbia River (Hartman & Ivarson, 2011).

Uranium: According to the EPA, uranium is chemically toxic to the bodies of humans and animals, and carcinogenic due to its radioactivity, with major impacts on the kidneys (Poston *et al*., 2009) (Riverkeeper, 2011). Uranium is extremely persistent with a half-life of 4.5 billion years (EPA, 2019). Due to its longevity in the environment, Hanford's uranium contamination poses serious threats to human and aquatic life in the Columbia River for generations. In the southern area of the Site, the DOE disposed of uranium in a crib and unlined trenches very close to the river (*Figure 3*) (Riverkeeper, 2011). Monitoring wells along the Columbia River show that uranium in the groundwater continues to exceed the drinking water standard by over 300% (*Figure 3, Figure 4*) (Poston *et al*., 2009). To address uranium contamination, the DOE proposed a strategy of "monitored natural attenuation"— leaving the waste in place to decay naturally. Through this natural attenuation approach, the DOE does not take any active steps to address the contamination and instead relies on natural processes such as dilution, adsorption, degradation, decay, and chemical reactions to reduce contamination (Government Accountability Office, 2006). This is problematic when the isotope is stable for 4.5 billion years and the plume is currently reaching the Columbia River. A scientific peer review panel and the Hanford Advisory Board considered

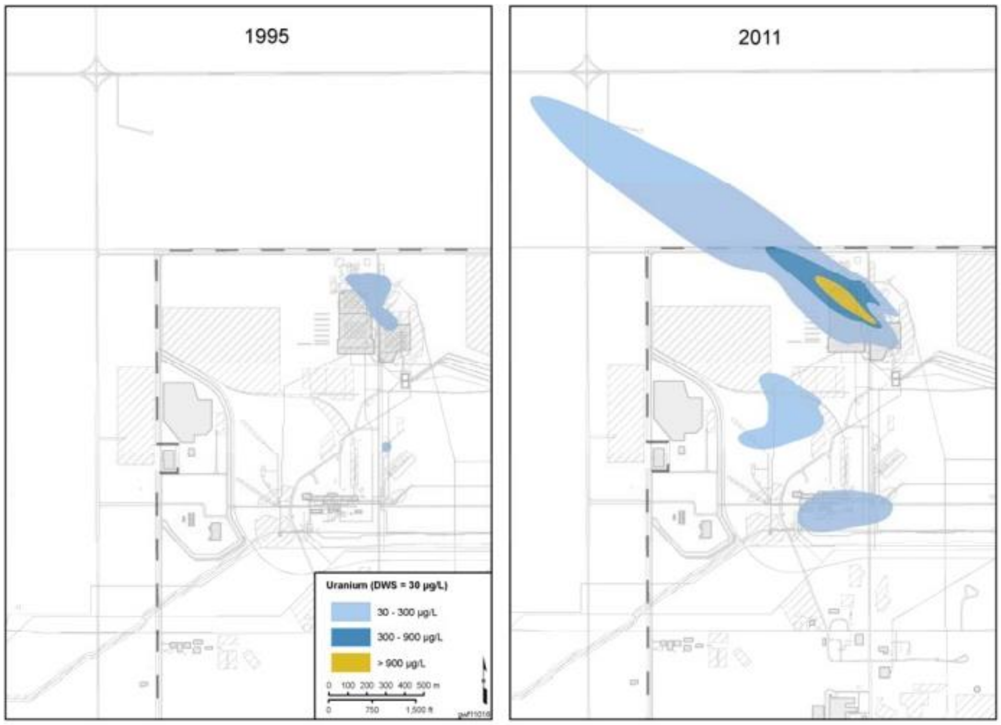


Figure 4: A uranium plume began to develop at the Hanford Site in the late 1990s, several years after the final reactor had been decommissioned. This isotope remains stable and persistent in the environment for 4.5 billion years. While there are no remediation strategies in place and previous attempts to neutralize the contamination with a pump-and-treat system did not succeed, the DOE is testing new methods and working on developing technology that can remove the uranium contamination from Hanford's soil and groundwater (Hartman & Ivarson, 2011). Images: Hartman & Ivarson, 2011.

the natural attenuation approach to be unrealistic, as the contamination plumes would continue to impact salmon spawning in the Hanford Reach, particularly incubating Chinook egg nests (redds) (Government Accountability Office, 2006). After feedback and further consideration, DOE is now evaluating more aggressive cleanup strategies (Poston *et al*., 2009).

The technology to properly treat and neutralize the uranium is still being developed. Cleanup of Hanford's groundwater uranium problem is necessary to mitigate the potential impacts to the Columbia River, its inhabitants, and the human population sourcing food from the water (Hanford Advisory Board, 2013). As of 2012 and 2013 reports, the science that had been developed and used to sequester and remediate uranium was found to be "not entirely successful in the near-river environment" (Leckband, 2012) (Hanford Advisory Board, 2013) (Vermeul *et al*., 2007).

Carbon tetrachloride: Carbon tetrachloride is carcinogenic and acutely toxic to humans. In a mixture with other organic compounds, the DOE used carbon tetrachloride to extract plutonium for nuclear weapons (Riverkeeper, 2011). Carbon tetrachloride is present in large quantities at the Hanford site, with extensive areas of groundwater– over four square miles– exceed drinking water standards (Pacific Northwest Laboratory, 1991). The DOE's projections show that, without aggressive cleanup, the plume of contamination could continue to enter the Columbia River at levels exceeding the drinking water standard for over 100 years (Truex *et al*., 2001), at which point the danger will increase (*Figure 5*). Carbon tetrachloride concentrations reaching the Columbia River will climb to 50 times the pollution standard in 125 years (Poston *et al*., 2009) (Riverkeeper, 2011).

Iodine-129: Long-term exposure to radioactive iodine-129 can cause thyroid cancer, and low doses inhibit activity of the thyroid gland. Large airborne releases of radioactive iodine from Hanford have been blamed for decades of thyroid illnesses, and are the subject of ongoing "down winder" investigations (Energy BC, 2012) (Riverkeeper, 2011) (DOE, 2009). Iodine-129 is a major concern in groundwater at Hanford because it is long-lived (*Figure 5*), leaking into the Hanford Reach of the Columbia River, where Chinook salmon incubate, rear, and develop in that water for one to two years before migrating out to sea (US Department of the Interior, 2019). Over 25 square miles of groundwater around the Hanford Reach are contaminated with iodine-129 at levels above drinking water standards, and the plume continues to shift closer the Columbia River (Riverkeeper, 2011).

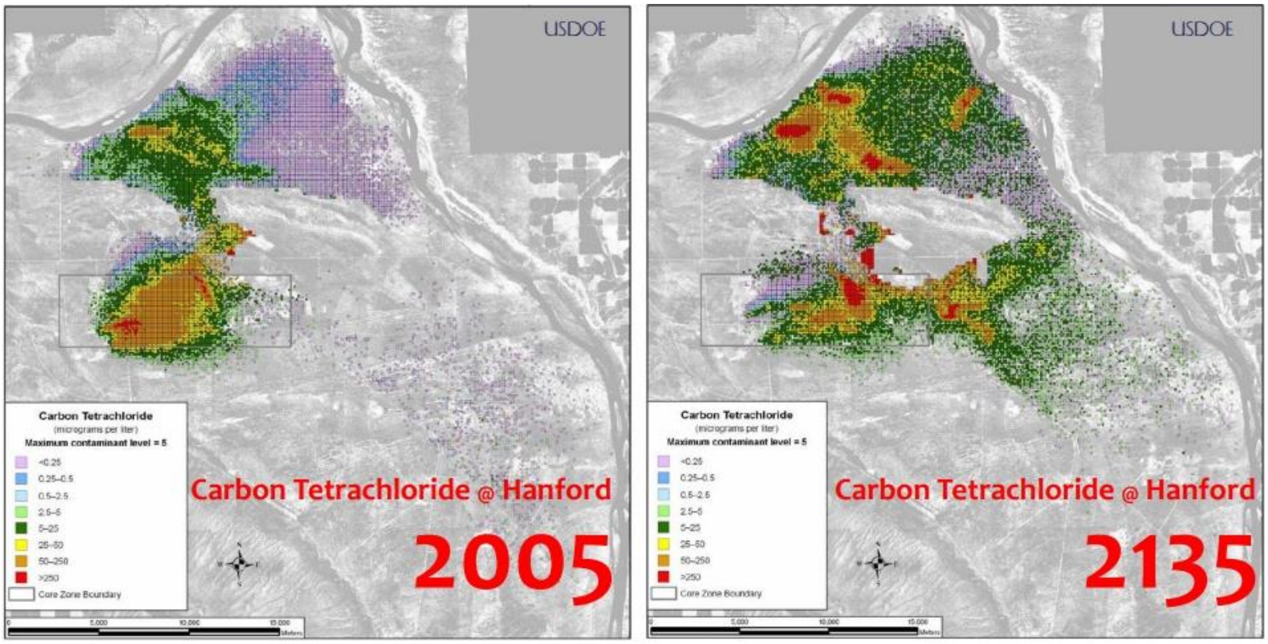


Figure 5: If left alone, the toxic waste problem at Hanford will not disappear any time soon. As storage tanks continue to degrade and groundwater plumes flow slowly toward the river, contamination like carbon tetrachloride will get worse (Hanford Natural Resource Damage Assessment Injury Assessment Plan, 2013). Without aggressive intervention, DOE's projections for carbon tetrachloride, uranium-238, iodine-129, and technetium-99 show a stable stream of contamination reaching the Columbia River thousands of years into the future (Riverkeeper, 2011) (DOE, 2009) (DOE, 2012). Carbon tetrachloride concentrations reaching the Columbia River will climb to 50 times the pollution standard in 125 years (Poston *et al*., 2009).

While uranium has a half-life of 4.5 billion years, after 240,000 years, it will undergo geochemical changes and begin to have less mobility, moving slightly slower within the groundwater. Iodine-129 will remain mobile and radioactive in the groundwater for 17 million years if not removed. Technetium-99 will remain mobile in groundwater plumes for 213,000 years (Hartman & Ivarson, 2011). A 2006 legal settlement required DOE to prepare annual Tank Closure and Waste Management Environmental Impact Statements for the Hanford Site to monitor these contaminants and share progress with the public (DOE, 2020). The final Environmental Impact Statement, which suggested an optimistic view on taking a less aggressive approach to cleaning up these long-lived contaminants, was published in 2012. It, along with previous years' Environmental Impact Statements, was disputed by the Hanford Advisory Board for being incomplete, presenting inadequate data or insufficient analysis to support the scientific decisions proposed in the Statement (Hanford Advisory Board, 2010).

Technetium-99: "Technetium-99 is one of the more volatile radionuclides" in the Hanford Reach area with a long half-life of 211,000 years, "coupled with the high environmental mobility [through groundwater]… makes technetium-99 one of the most significant risk contributors" for aquatic and human life in the region (Pegg, 2015). In aging underground tanks, the Hanford Site still holds approximately 24,000 Ci of leftover technetium-99 in about 56 million gallons of high-level waste from the production of plutonium for nuclear weapons (Pegg, 2015). In 2003, the DOE Office of River Protection announced the decision to eliminate technetium-99 pretreatment from the tank waste treatment plant with no technical analysis or scientific data to support the modification. The previous agreement, signed in 1989, resulted from a “detailed and thorough public vetting” by experts in those areas of science, and required technetium-99 pretreatment in the waste treatment plant. Elimination of the pretreatment impacted the concentration of technetium-99 in various waste discharge and process streams, resulting in more technetium-99 groundwater contamination (Martin, 2003) which was expected to affect the surrounding ecosystem. The short- and long-term impacts to the environment– including groundwater contamination and effects on aquatic life– of not removing technetium-99 from the waste are unknown and should be further analyzed (Martin, 2005) (Martin, 2002).

The DOE must, by law, clean up groundwater at the Hanford site to a level that meets state and federal drinking water standards; as well as meet *Dangerous Waste Permit for the Treatment, Storage, and Disposal of Dangerous Waste* criteria to protect environmental and human health during the construction, operation, cleanup, closure, and post-closure of Hanford Site facilities (Federal Advisory Committee Act, 2012). Continued upwellings of contaminants above regulatory levels into the Columbia River suggest that the Department is not meeting this requirement (U.S. Government Accountability Office, 2005) (Riverkeeper, 2011). The groundwater, which has a down-gradient flow from the Hanford Site to the river, contains pollutants that are highly toxic to river life, namely Chinook salmon and other fish, “at the cellular, biochemical, and genetic levels” including effects on fertilization, blood clotting function, decreased antibody production and increased susceptibility to bacteria, hyperglycemic responses, decreased cell viability, decrease in survival rate and growth rate, erosion of fin and fin rays, and DNA damage (Velma *et al*., 2009). Groundwater cleanup must remove pollutants to protect salmon (Riverkeeper, 2011).

Lab-Based Studies

Olson & Foster (1956) exposed laboratory Chinooks to known Hanford Site contaminant hexavalent chromium at concentrations of 0-184 µg/L for 7 months, starting at egg stage. While there was no significant mortality during egg stage, significantly fewer fish survived at the 80 and 184 µg/L concentrations than at any others by the end of fry stage. Growth retardation was considered “probably significant in the group exposed to 16µg/L”, and postulated to be “a more sensitive index of toxicity than mortality” at any stage. However, Olson & Foster’s experiments only tested exposure to up to 184µg/L of chromium, and Hanford Reach pore water– groundwater upwelling beneath the Columbia River– has measured as high as 632µg/L in shallow pools during the 1990s where Chinook eggs incubated (Hope & Peterson 1996), not to mention accidental or undetected leaks and toxic discharge from when the Site was active (Hanford Natural Resource Damage Assessment Injury Assessment Plan, 2013).

Despite contaminants like chromium being dangerous to salmon at concentrations (10 µg/L) well below the drinking water standard (100 µg/L), fish-safe strontium-90 levels are unknown and the government assumes the drinking water standard of strontium is protective of aquatic life (Riverkeeper, 2011). A study on the USA's Atlantic coast examined fish in the Savannah River after another DOE nuclear weapons production facility leaked contaminated water into the surrounding environment. Researchers recorded fish tissues bioconcentrating strontium-90 thousands of times above the concentrations in their ambient water, making similar concerns in Hanford Chinooks top priority (Poston *et al*., 2009) (ATSDR, 2012) (Riverkeeper, 2011). Meanwhile, *Figure 2* visualized plumes of strontium-90 flowing through Hanford groundwater, directly into the Columbia River at concentrations 1000 times greater than safe levels (Poston *et al*., 2009). If fish in other areas are known to bioaccumulate strontium into their tissue at many times the concentration of the water around them, and young fish in the Hanford Reach are exposed to groundwater upwellings contaminated with strontium many times the safe level for up to two years before migrating out to sea, it is reasonable to call for further data to be collected to establish a regulatory standard for strontium with regard to aquatic life. Additionally, exposure to high doses of strontium-90 by injection in laboratory animals led to significant reproductive effects including reduced fertility, reduced gonadal cellularity, and suppressed spermatocyte maturation (Centers for Disease Control and Prevention, 2004).

Farag *et al*. (2000) examined effects of chromium on early life stages (egg, to swim-up, to a holding period of 30 days after swim-up) to monitor development, physiological function, growth, and survival rates. Aqueous chromium concentrations of 5-120 µg/L showed alevins (newly spawned salmon still carrying the yolk) were tolerant to chromium exposure, until after the initiation of exogenous feeding and swim-up, where mortality increased dramatically (Hanford Natural Resource Damage Assessment Injury Assessment Plan, 2013). A 2006 study also by Farag found concentrations of 24 and 54 µg Cr/L for 105 days didn't affect growth or survival of Chinook parr, but when concentrations increased to 120 and 266 µg/L, survival was reduced in the 120 µg/L group, and both groups exhibited health impairments, including kidney lesions and biochemical changes (Farag *et al*., 2006) (Hanford Natural Resource Damage Assessment Injury Assessment Plan, 2013).

Early Hanford studies were concerned primarily with young Chinook salmon and steelhead trout. Eggs and young fish were exposed in laboratory settings to higher concentrations of effluent than were actually present in the river. Many died. However, Hanford scientists determined that the cause of death was not exposure to the radioactivity. The fish deaths were determined to be due mainly to the chemicals added to pretreat the cooling water and the increase in water temperature. The studies did not examine the long-term effects of pretreat chemical exposure in the fish (Becker, 1990). There have also been no multifactorial studies considering the interacting effects on varied levels of Hanford Site pollutants and chemicals, in addition to background radiation.

Geist (2000) proved that spawning salmon did not use areas in the Hanford Reach where upwelling had a contaminated groundwater source. They only used discharge zones where the upwelling source was surface water, which was either uncontaminated or contaminated to a lesser degree than Hanford groundwater. Another study found that healthy Chinook parr in a lab setting are capable of detecting and avoiding water with chromium concentrations of ≥54µg/L. Conversely, Hanford parr in a lab setting failed to avoid chromium concentrations of up to 266µg/L. “One potential implication of these findings is that [wild Hanford] salmon may not be capable of discriminating between contaminated and uncontaminated habitat when chromium is presented in undiluted groundwater. Under this scenario, life-stages of salmon utilizing this habitat may not be able to behaviorally mitigate their exposure” (DeLonay *et al*., 2001). Concentrations avoided by healthy Chinook salmon were similar to concentrations shown in laboratory studies to result in tissue accumulation in early life stage salmon (Patton *et al*. 2000), and were also within the range of concentrations known to result in physiological impairment in salmon parr (Farag *et al*. 2000).

Avoidance of environmental contaminants is an adapted behavior that often reduces exposure to contaminants through behavior that may limit contact with, or residence in, unfavorable or contaminated habitat (DeLonay *et al*., 2001). Significant behavioral avoidance of contaminated areas in the field may result in the substantial loss of important Chinook habitat in the Hanford Reach, impact reproduction, impair imprinting and homing behavior, and could have long-term, far-reaching effects on sensitive anadromous fish populations beyond just fall Chinooks. Meanwhile, failure to avoid contaminated areas in the Hanford Reach, or preference for contaminated areas, may result in increased exposure to hazardous substances leading to physiological impairment or death (DeLonay *et al*., 2001). The behavioral changes documented in Geist and DeLonay’s studies were used as evidence to constitute an injury classification under DOI’s NRDA regulations, and officially recommend additional research on Hanford Reach Chinooks as appropriate to assess spawning habitat safety. “Trustees are also considering a field-based (*in situ*) investigation of potential impacts on early life stages” (Hanford Natural Resource Damage Assessment Injury Assessment Plan, 2013). The same report also acknowledged that “organisms may sometimes experience adverse effects to contaminants under field conditions that aren't evident from lab-based exposures, conducted under much more controlled conditions" (Hanford Natural Resource Damage Assessment Injury Assessment Plan, 2013).

Field Studies

Approximately 75% of the Hanford Reach river corridor has been identified as currently or previously contaminated by nuclear waste. Concentrations above the 10 μg/L limit of hexavalent chromium were present in the unconfined aquifers of all 100 test areas of a 2013 study, with the highest plume concentrations being recorded in 2012 at approximately 960 times the 10 μg/L standard for fish safety. Hexavalent chromium contaminant plumes with concentrations above the 10μg/L surface water quality standard for Washington state are classified as a toxic substance. Remediation efforts at former nuclear waste disposal sites in Hanford show mobilized hexavalent chromium migrating to the upper part of the aquifer, requiring close monitoring in the future. Unsafe levels of several contaminants including tritium, strontium-90, nitrate, carbon-14, uranium, and trichloroethene were also identified in this river corridor study (DOE, 2013).

Field Studies: *Hatchery Supplementation*

The Hanford Site began plutonium production in 1943, discharging contaminated waste water into the Columbia, and "after a short lull, production was ramped up in 1947" (DOE, 2021). Dauble & Watson compared the spawning and abundance of fall Hanford Reach Chinooks from 1948-1988. Beginning in the 1950s, the size of the fall Chinook salmon run declined coincidently with loss and degradation of spawning habitat in Columbia River (Dauble & Watson, 1990). Chinooks which incubated, hatched, and reared in the Hanford Reach during the mid- to late-1940s when the Hanford Site was "ramping up" production (DOE, 2021) would have been returning to the Reach to spawn as 2-5 year old fish in the 1950s, indicating a possible relationship between contaminant introduction and a decline in Chinook numbers. Beginning in the early 1960s, juvenile hatchery Chinooks have been released into the Hanford Reach to supplement the declining natural stock, and the percentage of hatchery-originated fish in the fall runs of salmon have increased significantly over the decades, as the proportion of natural-origin adult Chinooks in returns have decreased (Richards & Pearsons, 2019). Salmon stock supplementation from Priest Rapids Hatchery– just upstream of the Hanford Site– and other hatchery sources added in the 1970s were credited for dramatically increased returns of adult fall Chinook salmon spawning in the Hanford Reach beginning around the 1980s. The relative contribution of hatchery salmon stocks to fall

Chinook salmon runs "increased from about 24% of the total in the early 1980s to 50-60% of the total by 1990" (Dauble & Watson, 1990).

Field Studies: *Heated Effluent Mitigates Harmful Effects on Salmon*

Chemistry and physics may explain why discharging of highly toxic Hanford Site effluent directly into the river between the 1940s and 1970s managed to have potentially fewer harmful impacts on the salmon than would be expected. Nuclear weapons production activities that threatened fall Chinook survival "included the release of heat, chemicals, and radionuclides through the discharge of reactor cooling water to the river, as and impingement and/or entrainment of fish at reactor cooling water intake structures" (Dauble & Watson, 1990). Major spawning areas in the Reach were subjected to untreated reactor effluents for several years, particularly between the late 1940s and mid-1960s, with salmon spawning noted within 100m of the outfall (*Figure 9*) (Watson, 1970). "However, because the heated effluents rose toward the river surface, influence on eggs and embryos that develop in the bottom substrate was reduced… Avoidance behavior may have also reduced the potential for juvenile salmon to be exposed to lethal temperatures from thermal plumes at the point of discharge" (Dauble & Watson, 1990) (Gray *et al*., 1977). While the general distribution of fall Chinook egg nests [hereafter referred to as redds] did not appear to change following the closure of reactors located immediately upstream from major spawning areas (Watson, 1970), and thermal discharges from reactors had no obvious effect on the upstream migration of Chinook salmon adults or on the downstream passage of juveniles (Templeton & Coutant, 1971), there was a decrease in the number of operating reactors between 1965 and 1969 that correlated with a "marked rise in numbers of salmon redds" (Dauble & Watson, 1990). In the earliest years of nuclear weapons production, the most contaminated water released from the Site was warm and therefore rose to the surface, potentially sparing redds along the bottom. Smolt survival during rearing and outmigration periods of those years was considered related to fish exhibiting avoidant behavior to escape heated discharge water- swimming deeper or farther away- and inadvertently circumventing the bulk of the radionuclides (Dauble & Watson, 1990). Had the toxic effluent not also been heated to lethal temperatures, salmon would have likely been more greatly affected and injured. Relatively healthy wild Chinook stocks emerging from this period are credited to a combination of the heated discharge water ascending above incubating salmon redds, adaptive avoidance behaviors, and hatchery supplementation efforts gearing up from the 1960s to 1980s (Dauble & Watson, 1990).

Field Studies: *Effects of Pollutant Exposure During Sensitive Life Stages*

A 2011 review found that discharges of contaminated Hanford groundwater into the Columbia River peak during the river's low-flow periods in fall and winter (Geist *et al*., 1994), and since these Chinooks spawn in the Hanford Reach in the fall, egg and fry development occurs during fall, winter, and into spring (Becker, 1973). Salmon, therefore, are most likely to come into contact with the toxic pollution during their most sensitive life stages— spawning and development (Geist *et al*., 1994) (Riverkeeper, 2011b). The same review detailed the effects of hexavalent chromium on early life stages of salmon. The Hanford Reach contains hexavalent chromium pollution, which the study identifies as being the most dangerous form of chromium (Geist *et al*., 1994) at levels over 1000% greater that the safe level (Hulstrom, 2010). Salmon and other aquatic life readily take up the hexavalent form of chromium, which is lethal at high concentrations near but slightly above the Hanford groundwater level (Geist *et al*., 1994). "Chromium can impact fertilization success by acting on fertilized eggs causing embryos to die" (Billard & Roubaud, 1985), "acting on egg and sperm individually, thereby impeding fertilization, impacting survival of early life stages, and reducing growth rates of juveniles" (Benoit, 1976) (Olson & Foster, 1956). Additionally, a 2001 report found that 84% of sampled Chinook in the Hanford Reach that physically appeared to be female tested positive for DNA indicative of a Y-chromosome. These feminized male fish may have resulted from exposure during early stages of development to contaminants, though it is unclear if the contaminants could have originated from the Hanford Site or other runoff and pollution of estrogenic mimickers, including detergents, plasticizers, and pesticides (Nagler *et al*., 2001) (Riverkeeper, 2011b).

Field Studies: *Superimposition of Redds and Epigenetic Impacts*

For the first 41 years of redd count data collection at the Hanford Reach, the same person– D.G. Watson– collected the data. Upon retirement, he wrote the guidelines and trained the next generation of researchers to ensure the same standard protocol would be followed. His recommendation for future research and analysis was to assess why seemingly ideal redd locations in the Reach are not being used by spawning salmon, while other areas are crowded with overlapping redds year after year. One of his suggestions was that perhaps there could be upwelling groundwater contamination in certain places that seem perfect to human eyes, but the fish know to avoid creating redds there. "Superimposition of redds in high use areas could disrupt egg pockets and reduce production in areas where suitable spawning habitat is limited," but perhaps it is more advantageous for Chinooks to overlap redds in high use zones if the alternative would be to utilize other areas that may be contaminated (Dauble & Watson, 1990). He also called for further evaluation of hatchery supplementation programs. "Increased hatchery production may be the only means of maintaining and/or increasing fall Chinook salmon production in the mid-Columbia River, particularly if current spawning areas are used at their maximum potential. Management of naturally produced populations may take on increased importance if hatchery supplementation strategies fail or if run size decreases. Genetic integrity of wild populations in the Hanford Reach could be threatened with increased hatchery supplementation" (Dauble & Watson, 1990).

As the push for hatchery supplementation to safeguard Hanford Chinook increases, there is a growing body of research demonstrating that supplementation may also cause a range of negative effects on the genepool of hatchery-stocked wild populations. These include the loss of genetic integrity, unintentional domestication selection, increased introgression from farmed escapees, epigenetic changes, reduced genetic variation, and reduced effective population size despite increased census population size– the Ryman-Laikre effect (Hagen *et al*., 2020). The Ryman-Laikre effect is a result of differences in reproductive success between captive and wild spawners, and when a large proportion of a population is made up of individuals that originate from a low number of captive parents– which is the situation with Hanford– the captive broodstock gives a disproportionate contribution to the population compared to wild spawners. This difference may decrease the number of effective breeders, thereby decreasing the genetic diversity, and increase genetic drift in the recipient population, which in this case would be the wild Hanford Reach Chinook population (Hagen et al., 2020). To confirm if this is happening in Hanford, a genetic study would have to be conducted of the wild and hatchery Chinook, but the fact that hatchery fish in Hanford were originally taken from the wild Hanford Chinook population does not matter. Growth in captivity for even one or two generations can cause genetic and epigenetic domestication effects that make hatchery-released individuals less adapted to natural conditions (Hagen et al., 2020). Hatchery-originated Chinooks comprised 24% of the total fall salmon run in the early 1980s, and by 2016, 93.6% of the Chinooks returning to spawn in the Hanford Reach were of hatchery origin (*Figure 10*). Over time, increasingly hatchery-originated fish continuing to make up the majority of the wild population could cause instability to the already-vulnerable and regionally vital Hanford Chinook population.

As mixing hatchery and wild Chinooks in the Hanford Reach may be contributing to an increasingly stressful genetic situation, another angle to consider is transposable elements (TEs), or "jumping genes". "TE activation is triggered by or in response to environmental stress", and in the best case scenario, "stress-activated TEs might generate the raw diversity that species require over evolutionary time to survive stressful situations" (Casacuberta & Gonzalez, 2013). Massive activation of TEs can be triggered by sudden placement in a new, stressful environment, which has been documented to "contribute to major genome rearrangements that would allow this organism to respond rapidly to changing environmental conditions", for better or for worse (Casacuberta & Gonzalez, 2013). One of the clearest cases of TE activation due to the breakdown of repression mechanisms brought on by environmental stress, is hybrid dysgenesis, "a sterility syndrome caused by very high rates of transposition of normally inactive TE families" (Casacuberta & Gonzalez, 2013). TEs induced from environmental conditions are passed from parent to offspring, and "the capacity to transpose and increase in copy number in a new invaded genome has been reported in several organisms including mammals, reptiles, fish, invertebrates, and insect viruses" (Casacuberta & Gonzalez, 2013). It is possible that releasing hatchery-grown Chinooks into the Columbia River where they suddenly have to compete with wild fish, find their own food, avoid predators, and swim through the contaminated Hanford Reach to the ocean may be enough environmental stress to trigger TEs, but a genetic study to test this has not yet been conducted.

Watson & Dauble's 1990 review pressed the importance of developing effective methods to predict exposure scenarios of incubating Chinook redds which are downstream or in upwelling areas of Hanford Site contaminants. Following the shut-down of the final nuclear reactors in the late 1980s, emphasis at Hanford shifted from nuclear fuel production to cleanup of existing waste sites, which Watson levied should include procedures for testing long-term effects of migrating nuclear waste materials on Hanford Chinooks and their habitat, especially in vulnerable early stages of development (Dauble & Watson, 1990). In addition to direct effects of Hanford Site contaminants, as well as possible outside influence from other point sources of pollution like endocrine disruptors from the surrounding area that could alter sex ratios [see Data Analysis: *Sex Ratios* section]; considering the epigenetic impacts of a potential Ryman-Laikre effect and TEs interacting between hatchery a wild populations may also provide a more complex but complete explanation for what is happening with Hanford Chinooks.

Stress-induced transpositions in the genome can also alter sex ratios of a population, and one documented source of stress activating TEs is when different species, populations, or stocks are crossed and the repression of TEs is lost. The sex determining gene in salmon is subject to transposition, sometimes causing genotypic males to present as phenotypic females (Kijas *et al*., 2018) (Ayllon *et al*., 2020a&b). "TEs are present in roughly all genomes. These mobile DNA sequences are able to invade genomes and their impact on genome evolution is substantial. The mobility of TEs can induce the appearance of deleterious mutations, gene disruption, and chromosome rearrangements", but transposition activity can also have positive aspects if the mutational activities of TEs contribute to the genetic diversity of an organism (Chenais *et al*., 2012). Eventually TEs may result in adaptation to a new environment if the species or population survives long enough, but the interim consequences such as loss of fecundity or sex ratio distortion can be catastrophic for the short term. Additionally, TEs were found to integrate close to genes induced by specific stress conditions, such as cadmium and heat exposure (Casacuberta & Gonzalez, 2013) (Ovelgonne *et al*., 1995), and since heatshock and cadmium exposure are known to have affected Hanford Reach Chinooks in the past (Keller & Stewart, 1991) (Dauble & Watson, 1990) (Gray *et al*., 1977), it is possible that TEs could have been activated that way.

Field Studies: *Hydroelectric Dams*

Between 1938 and 1967, 11 hydroelectric dams were constructed on the Columbia River both up- and downstream of the Hanford Reach. These dams now block access or inundate most spawning sites used historically by fall Chinook salmon in the mainstem Columbia River. As a result, productive Chinook spawning areas in the river were essentially condensed to the Hanford Reach, and that has not changed (Dauble & Watson, 1990) in over 54 years. Because the dam constructions took place either before or shortly after the study period in question (1948-2021), they are not considered a major factor in affecting Chinook data over the past few decades. Daily and seasonal hydroelectric dam flow fluctuations are also not recognized as a heavy influence in Hanford Chinook health parameters considered for this review. Discharge over Priest Rapids Dam– which is upstream of the Hanford Reach– varies daily and seasonally, but almost always stays within the range of 50-100ft3/sec x 100 (Dauble & Watson, 1990). Therefore, short-term fluctuations in river flow that expose Chinook redds above the water’s surface often do not negatively impact the survival of developing salmon in the gravel. Adequate ground water upwellings– known as bank storage– are available to maintain intergravel flows across the redds when hydroelectric dams briefly reduce river flow. Pre-hatch stages of salmonids are more tolerant to dewatering than post-hatch stages. Eggs and embryos can obtain oxygen from air by diffusion if moisture and temperature conditions are favorable (Dauble & Watson, 1990). The largest contributor to river flow fluctuation is the Grand Coulee Dam, which is over 200 miles upstream of Hanford (Foundation for Water and Energy Education, 2020) and finished construction in 1941 (Dauble & Watson, 1990), two years before the Hanford Site began production, and seven years before the earliest Hanford Chinook data in question was collected. The oldest Chinooks returning to the Reach to spawn are around 5 years old, but usually younger, especially in recent years (Harnish, 2017) (Heffernan, 2021), so the seven year gap between the Grand Coulee Dam and the earliest Hanford Chinook data eliminates the dam constructions as a major influence on salmon health.

Additionally, “constraints placed on flow fluctuations from Priest Rapids Dam [just upriver from Hanford]… appear to have been effective at increasing both productivity and carrying capacity of the Hanford Reach fall Chinook salmon population” (Harnish, 2017). As of 2020, Columbia River hydroelectric dam operators were required to manage flows to protect the thousands of salmon redds in the Hanford Reach each year. “With our ability to use the hydro system to protect the salmon during the winter and spring, we have practically doubled the amount of spawning habitat and ensured that it will stay wet compared to what it would be without the hydro system. This is a great example of collaboration to benefit wild fish and it’s helped produce one of the region’s healthiest wild salmon runs” (Bonneville Power Administration, 2020). Management strategies that have proven successful for increasing survival of juvenile fall Chinooks include maintaining higher river flows during smolt outmigration, installing screens to bypass downstream migrants past turbines, and transporting smolts by barge and/or truck past downstream dams. “Collection and loading for transport stresses juvenile salmon, but this is not perceived as a problem for fall Chinook salmon” (Maule *et al*., 1988) (Dauble & Watson, 1990).

Data Analysis

Reliable data on wild Hanford fall Chinooks and their environment was limited. Suitable data that was available for consideration was compared spatio-temporally. For example, annual nest (redd) counts in the Hanford Reach were conducted by the same biologist for over 40 years– even using the same aircraft and data sheets every year to conduct the counts– who then wrote the guidelines for conducting red counts and personally trained the next generation of researchers. Consistency in redd counts from year to year was still not found to be reliable. “Estimates can be expected to vary between observers. For example, in one study of salmon spawning, a lack of precision between observers resulted in variances of +50%” (Bevan, 1961) (Dauble & Watson, 1990). With this in mind, available parameters for data analyses were sex ratios by brood year (*Figure 6*), successful upriver passage of adults over dams (escapement) vs resulting redd counts (*Figures 7, 8*), wild-origin vs hatchery-origin survival in the Hanford Reach (*Figure 10*), and fecundity vs body size (*Figure 11*).

Yakama Nation (Tribal) elders pushed and failed to secure more in-depth wild Chinook data collection. “We don’t have enough funding to conduct the needed testing on young salmon, to see how it affects them" (Tolson, 2014). Lack of sufficient wild Chinook monitoring was considered a breach of a 1989 legally-binding federal agreement and consent order signed by the government, prompting several attempts in court cases to make impartial research data publicly available. Regarding the full impact of Hanford contamination on salmon health, "we don't know, and they can't tell us as they are under contract to the DOE and bound to confidentiality" (Tolson, 2014). [Further information on the US federal government's involvement in data collection is available after the Data Analysis section.]

Data Analysis: *Sex Ratios by Brood Year*

A paper was previously mentioned in the Field Studies section that found 84% of phenotypically female wild Hanford Chinooks were actually male. The apparently feminized male fish were thought to have resulted from exposure to contaminants during early stages of development (Nagler *et al*., 2001), which the authors theorized would have likely been estrogenic steroids or estrogen mimickers, including detergents, plasticizers, pesticides, or other endocrine disrupting chemicals (Nagler *et al*., 2001). In other words, the authors supposed that it was not the main radioactive or chemical waste products leaking from the Hanford Site, but rather pollution from other sources such as agricultural and industrial runoff in the surrounding area. Thus, compounding impacts from pollution point sources or chemicals contained in runoff from irrigation returns– in addition to Hanford Site toxic waste– are a consideration when assessing the health and future of both the wild and hatchery populations of Hanford Chinooks. For example, there is evidence that fluoride and aluminum released from an aluminum plant downstream of the Hanford Site impacted passage time and survival of migrating adult salmonids (Damaker & Dey, 1984; 1986; 1989) (Dauble & Watson, 1990). Additionally, if epigenetic factors such as the Ryman-Laikre effect or transposable elements (TEs) are at play, the sex ratio distortions in Hanford Chinooks are a multi-layered topic to break down and potentially try to resolve.

Male to Female Ratios in both the wild and hatchery Hanford Chinook populations are shown in *Figure 6*. While both populations were female-biased, the hatchery (Priest Rapids Hatchery) fish were more female-biased than the wild fish. The main purpose of hatcheries in that area is to breed Chinooks that can be released and supplement the wild population, safeguarding the wild fish stock from becoming depleted. Wild Hanford Chinooks spawn on the banks of the Hanford Site, incubating redds in what would be potentially the highest risk areas for experiencing effects of Site contaminants. The majority of hatchery fish that supplement the natural Hanford population come from Priest Rapids Hatchery, which is upstream of the Site (Richards & Pearsons, 2019), in water that is believed to be unpolluted by Hanford nuclear productions waste.

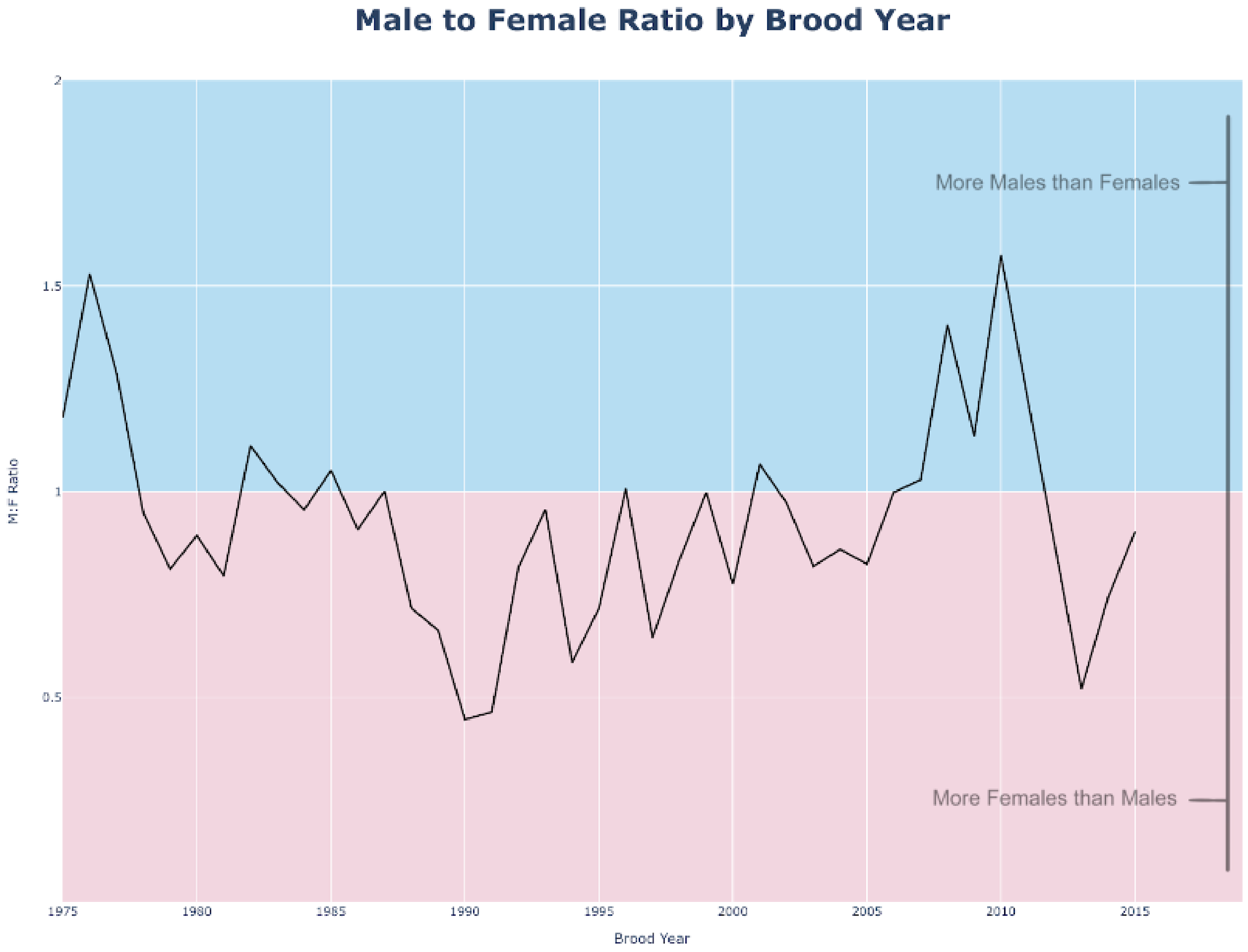


Figure 6: Male to Female Ratio of wild Hanford Chinooks from 1975 to 2015. Most years, there was a higher percentage of females in the population than males, with a mean M:F Ratio of 0.92. With 1 indicating a completely balanced M:F Ratio, numbers below 1 and approaching 0 (the pink section) indicate a more female-heavy population. Conversely, M:F Ratios above 1 and approaching 2 (blue section) indicate a more male-heavy population for that year. While the wild population had a mean M:F Ratio of 0.92, the female-biased discrepancy was significantly more pronounced in hatchery populations, which I calculated to have a mean M:F Ratio of 0.53, with all years' hatchery M:F Ratios falling between 0.44 and 0.65 (Richards & Pearsons, 2019). I assessed the Priest Rapids Hatchery populations, which are bred upstream of the Hanford Site in what is presumed to be less contaminated water, and released into the wild to spawn with natural-born Hanford Reach Chinooks each year.

Graph and caption were created using raw data calculated from (Harnish, 2017) and (Richards & Pearsons, 2019).

Widespread habitat destruction in other parts of the Columbia River– unrelated to the Hanford Site– has increased the importance of the Hanford Reach to spawning fall Chinook salmon since the 1950s. Natural production has been sustained with the help of extensive hatchery supplementation; "however, it should not be assumed that runs can be maintained with present management strategies" (Dauble & Watson, 1990). Supplementation from Priest Rapids Hatchery stocks are keeping the wild Hanford Chinook population– which already has a female-biased population– at healthy numbers. This hatchery is in water thought to be minimally affected by Hanford Site chemicals, but it is affected by other pollution point sources and chemical runoff thought to possibly be creating a heavily female-biased population with a M:F Ratio of 0.53 (*Figure 6*). The study that found 84% of female-presenting wild Chinooks were genotypic males, also found that female hatchery fish did not exhibit this sex reversal or male feminization (Nagler *et al*., 2001), indicating that the heavily female-biased M:F Ratio in Priest Rapids Hatchery is a true sex ratio discrepancy, while the slightly female-biased M:F Ratio of wild Chinooks depicted in *Figure 6* may actually be much less female-biased than it appears. Additionally, phenotypically "female salmon with a male genotype have been sex reversed, creating the potential for an abnormal YY genotype in the wild that would produce all-male offspring and alter sex ratios significantly" (Nagler *et al*., 2001). Nagler's study genetically tested the salmon to determine sex, but all other existing annual sex ratio data that the government uses to create sex ratio data– and that I used to create *Figure 6*– is based on sexing salmon by their phenotypic appearance.

It was the opinion of Nagler *et al*. that the sex ratio discrepancy was likely a result of an endocrine disrupting chemical released from a point source near the hatchery, upstream of Hanford, resulting in the highly female-biased hatchery population, and also resulting in feminization of wild fish when the hatchery Chinooks breed with the wild Chinooks, creating female-presenting genetic males. While that may be possible, at the time of Nagler's publishing in 2001, research on the Ryman-Laikre effect and transposable elements (TEs) altering the sex ratios of a population did not yet exist. In light of subsequent genetic findings that TEs make up as much as 85% of eukaryotic genomes (*Chenais* et al., 2012), it is less likely that undetected exposure to unknown endocrine disrupting chemicals is the sole culprit behind the Hanford Chinooks' sex ratio disturbance, and more likely that there was a loss of transposon suppression in the Chinook genome.

Data Analysis: *Escapement vs Redd Counts*

Figures 7 and *8* compare available data on adult Chinook escapement with peak annual redd counts across eight decades. Escapement is the number of adult Chinook who successfully make it upriver to spawn each year– who escaped predation and commercial fisheries during their years in the ocean, escaped over the fish ladders of hydroelectric dams, escaped the jaws and claws of hungry bears standing in the river during the upstream salmon migration, and made it to the Hanford Reach to procreate. There is a positive correlation between increasing escapement numbers and increasing redd counts (*Figure 7*), but a limit does exist for the productivity potential of the Hanford Reach (*Figure 8*). When more Chinook make it to the Hanford Reach to spawn (higher escapement years), there is a higher number of resulting egg nests observed in the Reach later in the season (higher redd counts).

Ever-increasing hatchery supplementation has resulted in higher escapement in recent decades, identifying that there is likely a ceiling for the number of superimposed redds that the Reach can support. *Figure 9* visualizes known "good years" and "bad years" with possible effects on redd counts. Additionally, a study found that years with high escapement resulted in more superimposition– or overcrowding– of redds in high-use areas of the Reach (*Figure 8*), and the superimposition is thought to be an avoidance behavior to evade contaminated upwelling zones in redd-free areas of the Reach (Dauble & Watson, 1990). The superimposition inadvertently results in egg pocket disruption (Dauble & Watson, 1990) and leads to later hatchings, smaller subyearling smolt sizes (fork lengths), later migrations out to the ocean, more outmigration predation, and lower smolt survival (McMichael *et al*., 2015). In short, extremely high escapement years result in lower smolt survival later in the season.

Redd Count & Escapement Correlation

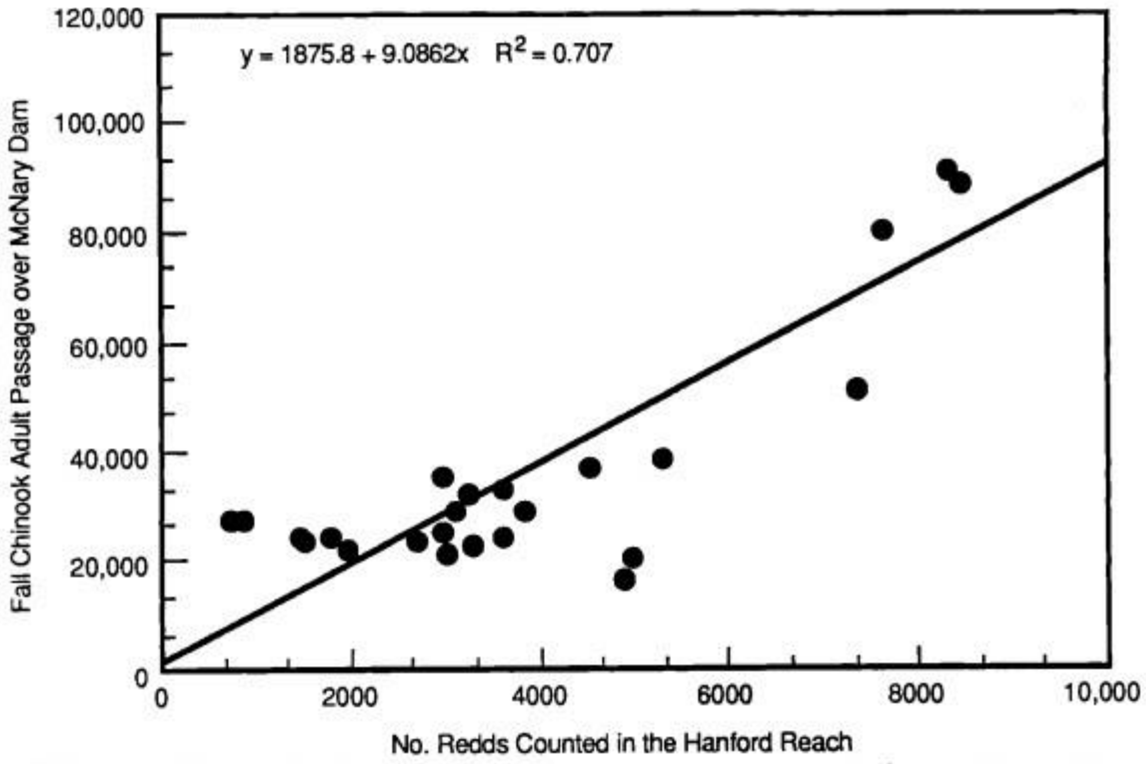


Figure 7: Relationship between adult escapement over McNary Dam (just downstream of the Hanford Site), and resulting Hanford redd counts. When more adults make it to the Hanford Reach to spawn, there is a positive correlation with the number of incubating redds observed later in the season.

Data and image from (Dauble & Watson, 1990).

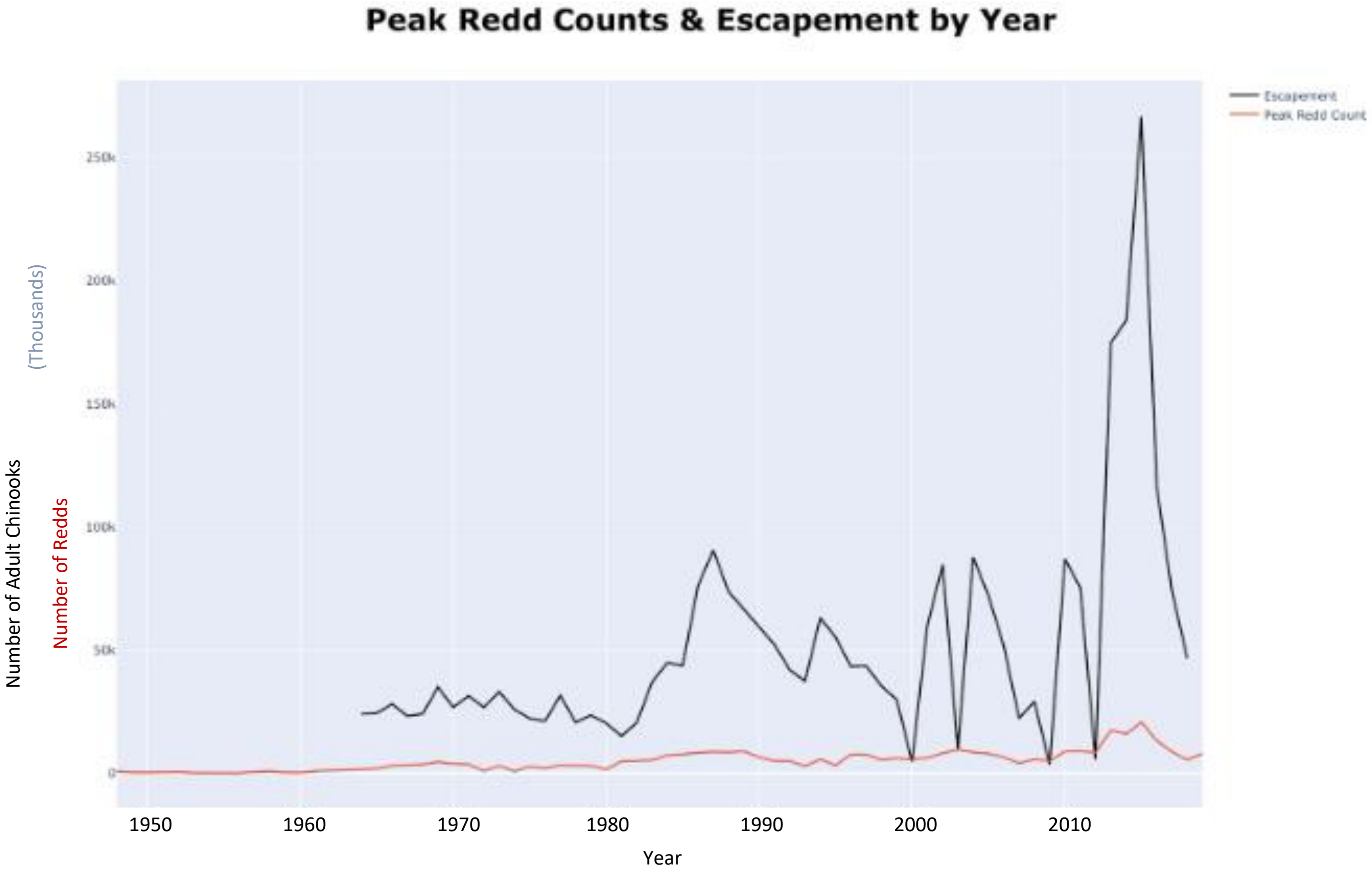


Figure 8: In general, as escapement increases, redd counts increase. There is, however, a limit to the number of redds that the Hanford Reach can accommodate between the McNary Dam (downstream of the Hanford Reach) and the Priest Rapids Dam (upstream of the Hanford Reach). While many areas in the Reach are utilized and even over-utilized by spawning Chinooks to maximum capacity with overlapping nests, other seemingly ideal redd locations on the outskirts of those areas are not used. After approximately 50 years of studying Hanford Chinook spawning behavior, D.G. Watson (Dauble & Watson, 1990) suggested that certain areas of the Reach that may appear as ideal redd locations to human eyes are particularly affected by upwelling groundwater contamination and therefore not utilized by spawning salmon. The fish appear to avoid creating redds there and instead superimpose nests in high use areas, eventually disrupting egg pockets and creating a ceiling for production. Thus, in the late 1980s, early 2000s, and 2014; greatly increased escapement numbers can be seen correlating to only slightly increased redd counts on the graph.

Data analyzed from (Nugent, 2016) (Richards & Pearsons, 2019) (Dauble & Watson, 1990).

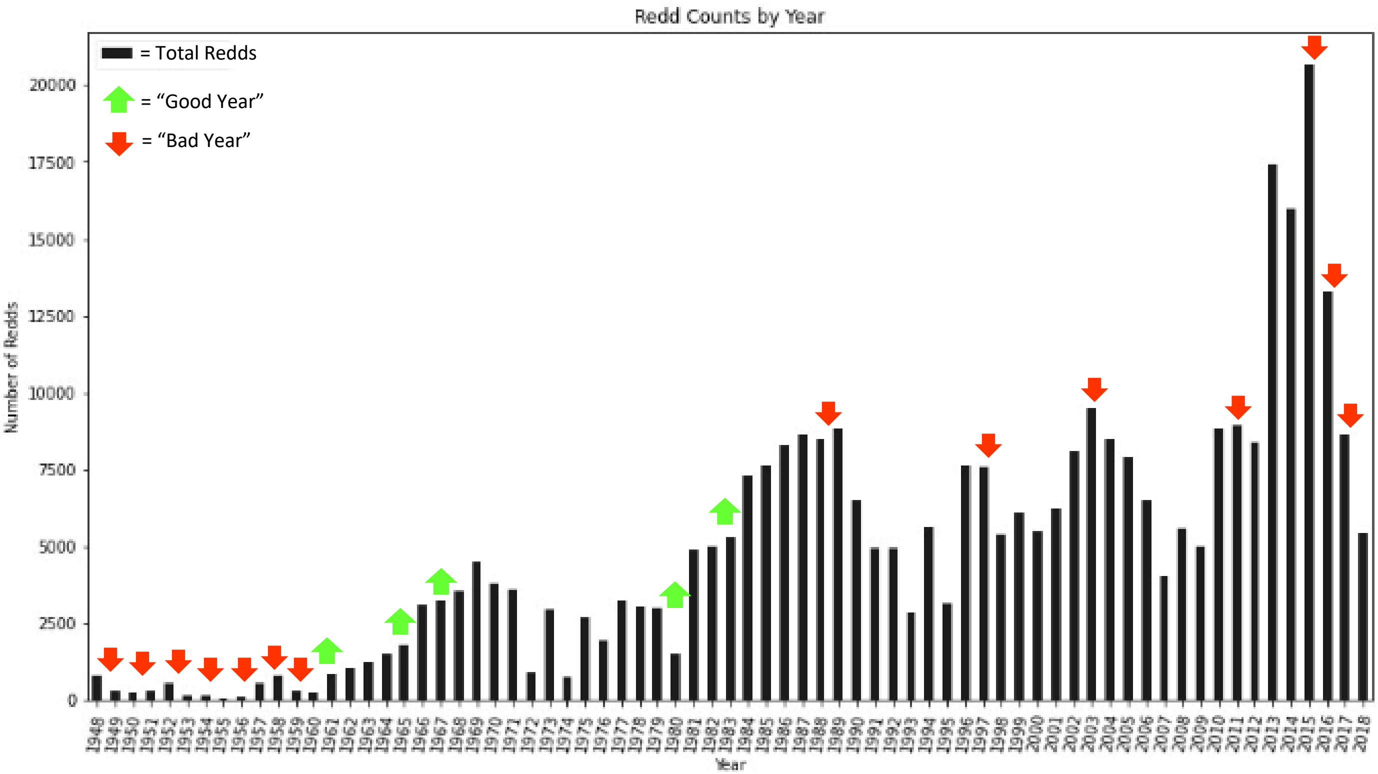


Figure 9: Annual Hanford Reach redd counts from 1948-2018, with possible correlations to known contamination leaks, spills, and hatchery supplementation efforts. Known "bad years"– represented in red– were 1944-1960 (highest number of reactors discharging untreated effluent directly into the river), 1988 (aluminum and fluoride leak from upriver dam), 1997 (radiation seepage increase from underground tanks), 2003 (contamination leak), 2011 (small increase in radioactive pollution), 2015 (contamination leak), 2016 (contamination leak), and 2017 (toxic waste leak). Known "good years" – represented in green– were 1961 (hatchery supplementation began), 1965-1969 (decrease in nuclear reactor operation), 1980 (hatchery supplementation practices drastically improve), and 1983 (increased number of hatchery suppliers).

Overall, redd counts have increased over the decades as hatchery supplementation has increased and as Hanford Site operations ceased. Also, the years on the far left side, 1948-1960, were during the time that several nuclear reactors were discharging lethally-heated water directly into the river where salmon redds incubated (Watson, 1970). Noticeably lower redds were observed in those years, but because the heated effluent rose toward the river surface, influence on eggs and embryos developing in the bottom substrate was mitigated. Avoidance behavior may have also reduced juvenile salmon exposure to lethal temperatures from thermal plumes at the point of discharge (Dauble & Watson, 1990) (Gray et al., 1977).

Data analyzed from (Nugent, 2016) (Richards & Pearsons, 2019) (Dauble & Watson, 1990) (Brown, 2017) (Brodeur, 2006) (WPSR, 2006) (Smith *et al*., 2015).

Data Analysis: *Hatchery Supplementation of Wild Population, & Wild-Origin vs Hatchery-Origin Survival*

Since the early 1960s, juvenile hatchery Chinooks have been released into the river to supplement the declining natural stock of wild Hanford Chinooks. The percentage of hatchery-originated fish in the fall runs of salmon have increased significantly over the decades, as the proportion of natural-origin adult Chinooks in returns have decreased (Richards & Pearsons, 2019). Salmon stock supplementation from hatcheries was credited for dramatically increased returns of adult fall Chinooks to the Hanford Reach beginning around the 1980s. Hatchery-originated Chinooks increased from 24% of the total fall salmon run in the early 1980s to 50-60% of the total by 1990 (Dauble & Watson, 1990), to over 93% by 2016 (*Figure 10*). *Figure 10* breaks down the percentage makeup of fall salmon runs, which is considered a measure of wild-origin vs hatchery-origin survival.

Figure 10: Origins of returning adult Chinooks for return years 2005-2018. Hatchery-originated Chinooks comprised 24% of the total run in the early 1980s, 50-60% of the total by 1990, and 93.6% by 2016. This indicates that wild-origin Chinooks, who incubated in redds along the Hanford Reach, are surviving and returning as adults in very small numbers when compared to hatchery-origin Chinooks who incubated upstream of the Hanford Site in water unaffected by nuclear waste contamination. This indicates that environmental conditions in the Hanford Reach are somehow negatively affecting a large portion of young wild salmon such that many do not survive into adulthood to then return to spawn.

Data analyzed from (Richards & Pearsons, 2019) (Dauble & Watson, 1990).

Data Analysis: *Fecundity and Body Size*

Figures 11A-D cover the positive linear relationship between fecundity and body size (fork length) in both hatchery-origin and wild-origin Chinooks. Richards & Pearsons' 2019 report found that larger mothers (longer fork lengths) have inherently larger body cavities; and therefore heavier, more numerous, and more voluminous eggs. Both wild-origin and Priest Rapids Hatchery-origin fish exhibited this trend, but the relationship in wild fish was slightly stronger. Chinook health parameters like fecundity particularly matter when determining if fish hatched in higher radiation years have lower fecundity when it comes time for them to spawn. Unfortunately, if there is raw data on average fecundity per year across the decades, it has not been made publicly available for further analysis and comparison with “good” and “bad” contamination years.

Body Size and Fecundity

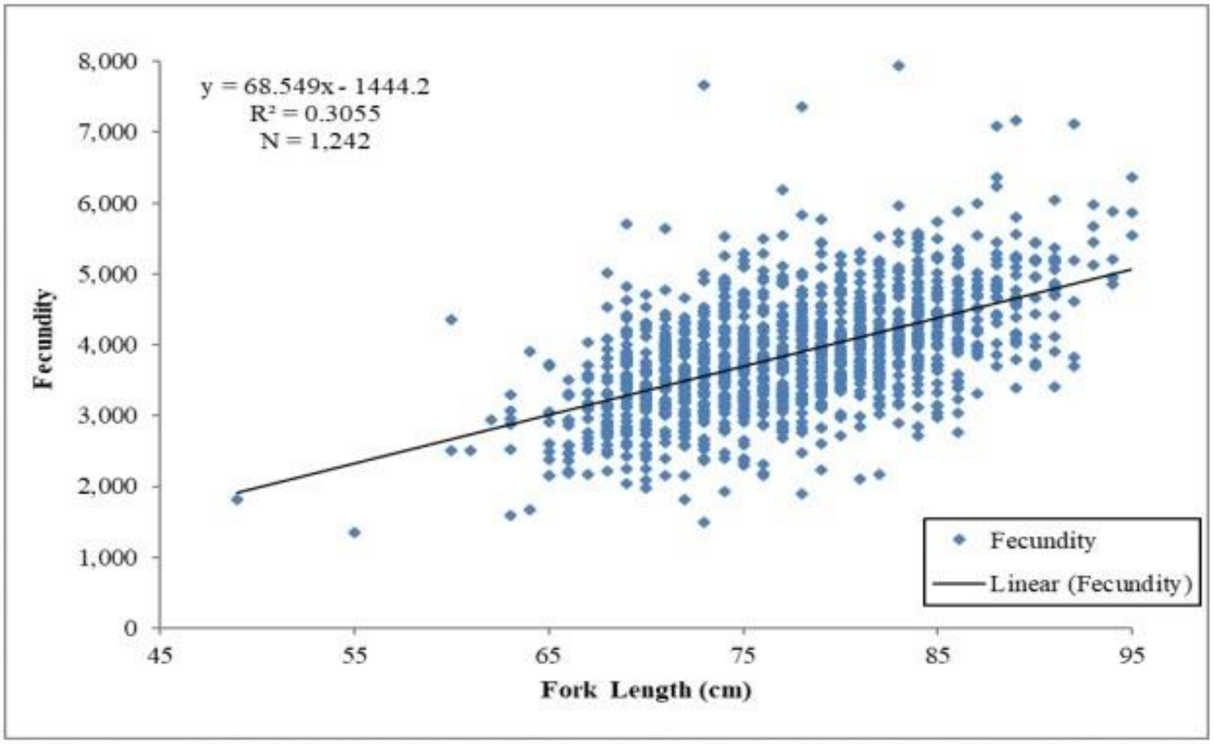


Figure 11A: Positive linear correlation between fecundity and fork length for combined samples of wild-origin and Priest Rapids Hatchery-origin fall Chinook for return years 2010-2018.

Image and data from (Richards & Pearsons, 2019).

Fecundity vs Body Size

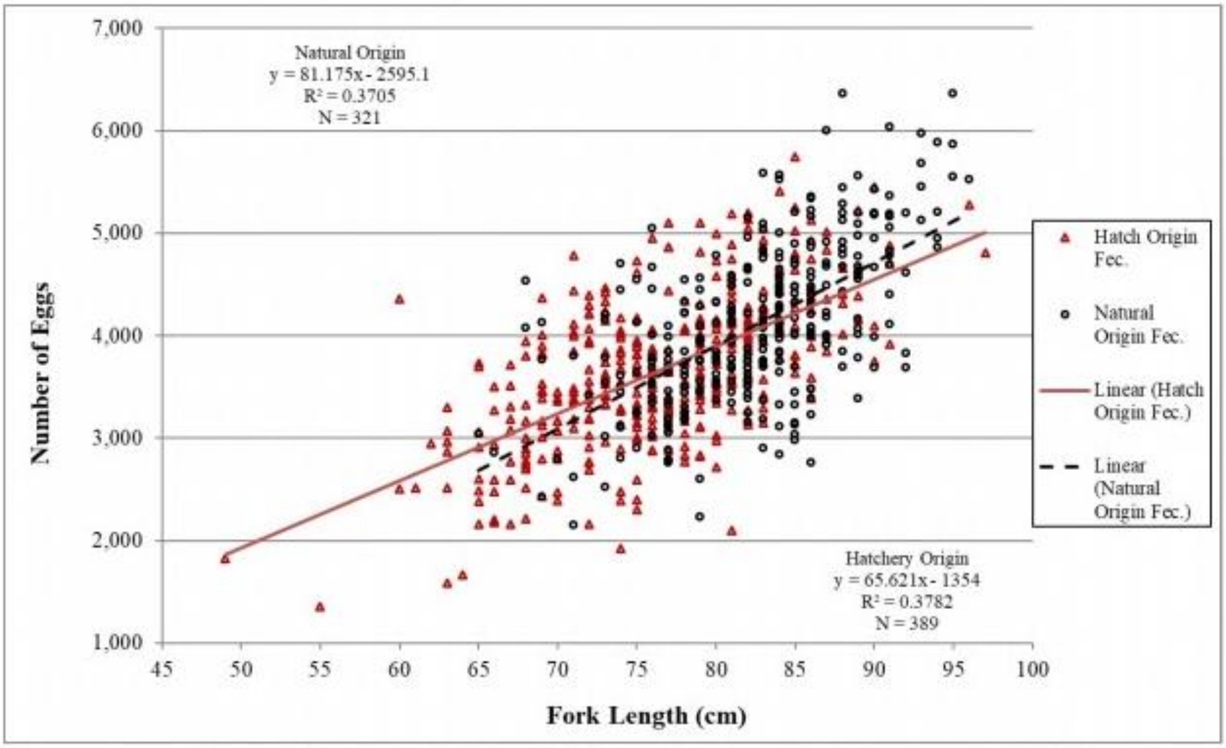


Figure 11B: Fecundity vs Fork Length for wild and Priest Rapids Hatchery-origin fall Chinook for return years 2013-2018. As the female's body size increases, the number of eggs she produces also increases. The wild-origin fish, seen in black, have an even stronger positive correlation between body size and number of eggs.

Image and data from (Richards & Pearsons, 2019).

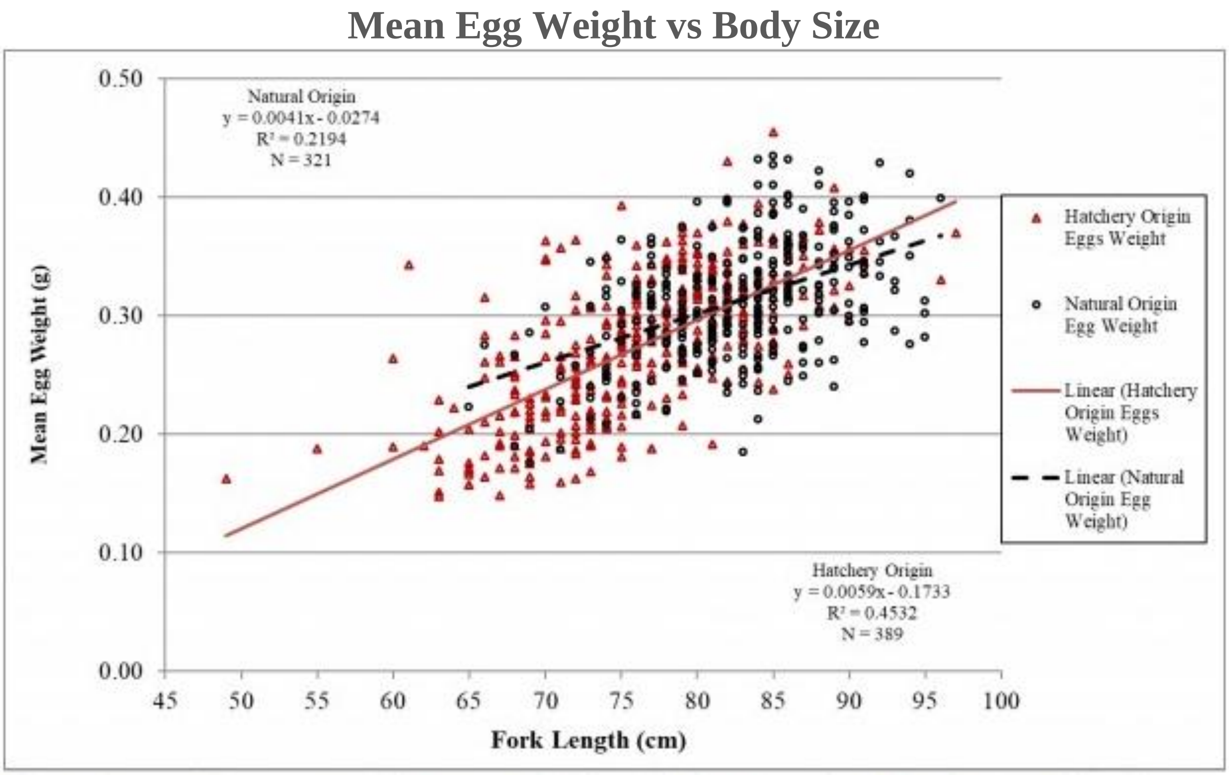


Figure 11C: Mean egg weight vs body size for natural and Priest Rapids Hatchery-origin fall Chinooks for return years 2013-2018. As body size of the mother increases, the mean egg weight also increases.

Data and image from (Richards & Pearsons, 2019).

Skein Weight vs Body Size

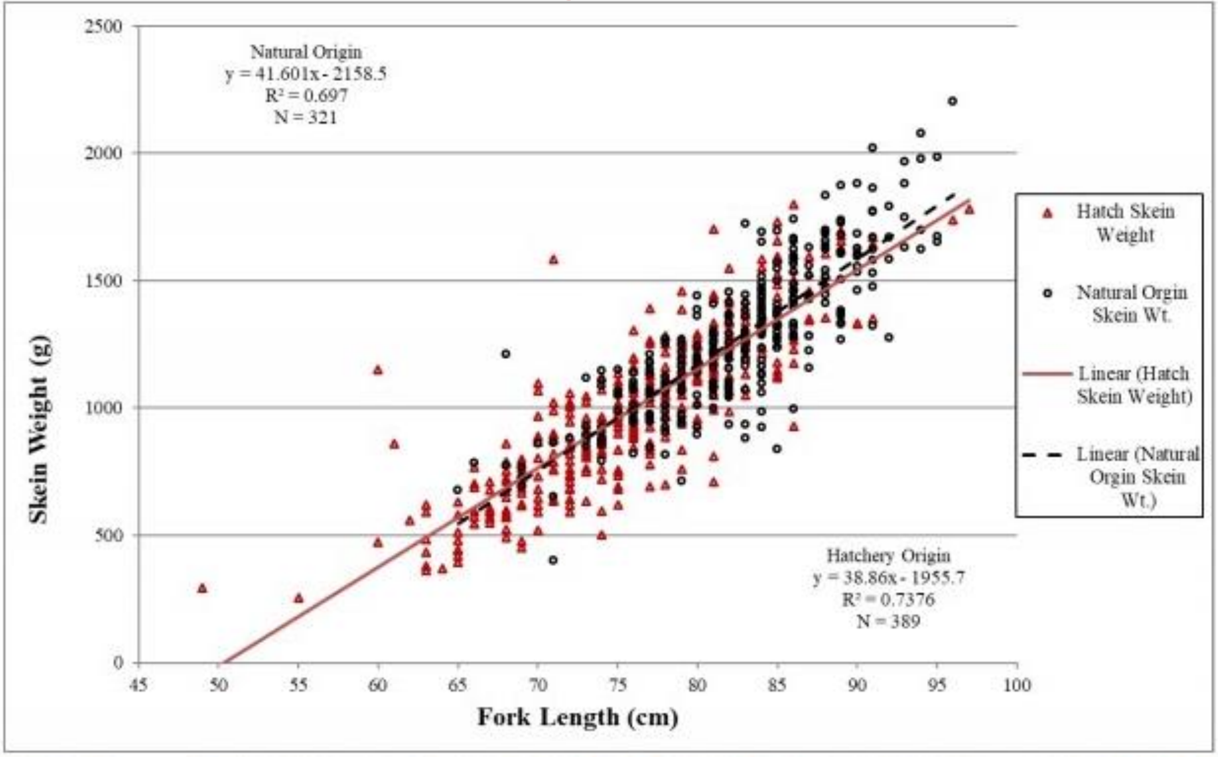


Figure 11D: Total egg mass (skein) weight vs body size of natural and Priest Rapids Hatchery-origin fall Chinook for return years 2013-2018. There is a positive linear relationship between increasing fork length and increasing skein weight. Larger females have larger body cavities and are therefore able to hold more numerous and more voluminous egg masses.

Data and image from (Richards & Pearsons, 2019).

A 2021 study by the Coastal Conservation Association identified a reduction in average age of returning Chinooks, resulting in “smaller” and “less reproductively fit fish” (Heffernan, 2021). Pit tags are injected into the snouts of juvenile hatchery-raised salmon so they can be tracked after release. Since the salmon runs are increasingly comprised of hatchery-origin fish (*Figure 10*), a nearly 50 year trend was established in declining age, size, and therefore fecundity (*Figure 11*) of fall Chinooks. “The difference means fish are smaller by several pounds and potentially less fertile” (Heffernan, 2021). Younger fish returning means smaller fish, which means smaller body cavities, which means lower fecundity (*Figure 11*). This supported my findings from analyzing a smaller amount of similar data (*Figure 12*), which indicated an increase in younger adult fish escapement into the Hanford Reach since the mid-1970s. Additionally, another study found that fecundity for the 2018 Priest Rapids Hatchery broodstock of Chinooks was lower than the historical mean, as well as identified a decline in size and associated fecundity of Chinooks along the entire west coast of North America (Ohlberger *et al*., 2018) (Richards & Pearsons, 2019).

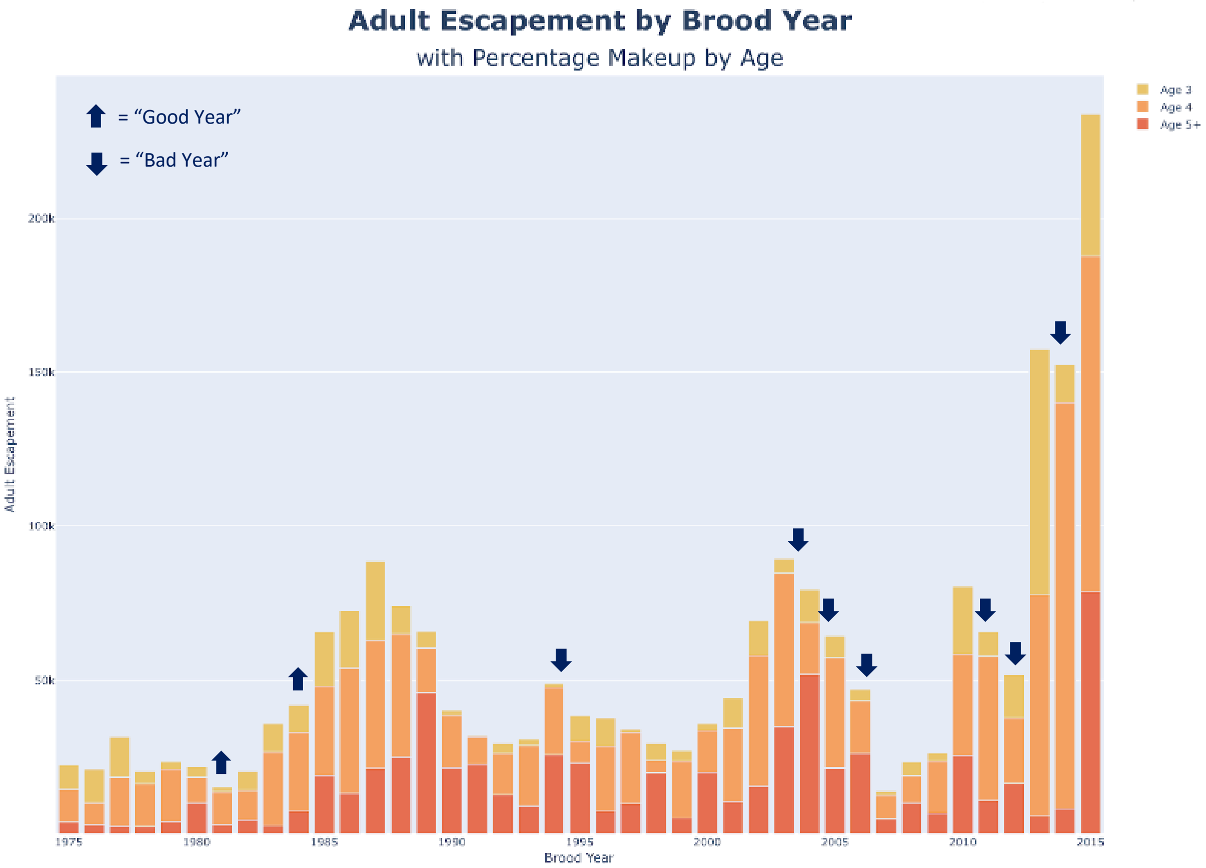


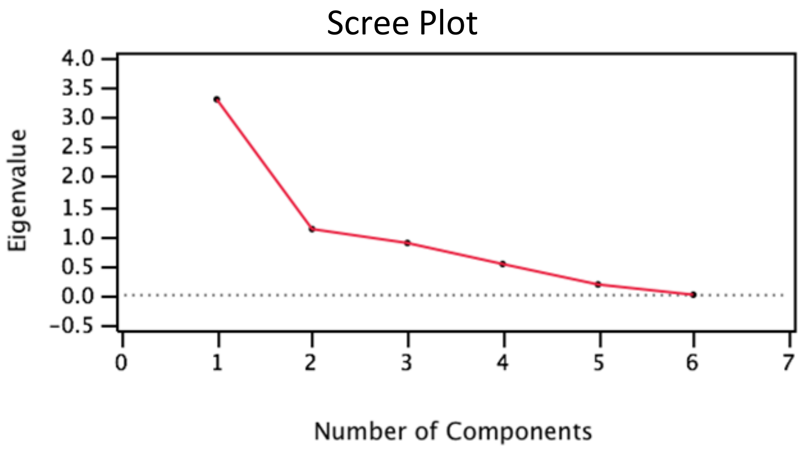
Figure 12: The age composition of adult escapement for brood years 1975-2015, showing younger fish (seen in yellow and orange) increasing over time. Though Heffernan's 2021 report uses pit tags and a larger dataset to prove the age reduction more clearly than the graph above, these escapement numbers show another possible relationship between "good" hatchery supplementation years and "bad" contamination leak years, with escapement size. Good years were 1981-1987 (drastically improved hatchery supplementation practices). Bad years were 1995-1999 (contamination leak), 2004-2007 (contamination leak), 2011 (slight increase in radiation), 2012 (hexavalent chromium plume spike), and 2014 (increased contamination upwellings in areas of the Reach where juvenile Chinooks gather).

Adult escapement is able to be directly considered in relation to Hanford Site contamination when measured in terms of brood year. By using brood year as the metric for time (the year those adult fish were "born" and incubated in Hanford waters), it can be directly compared with the resulting escapement to identify how many actually survived and made it back, as well as possibly identify years with previously undetected contamination leaks.

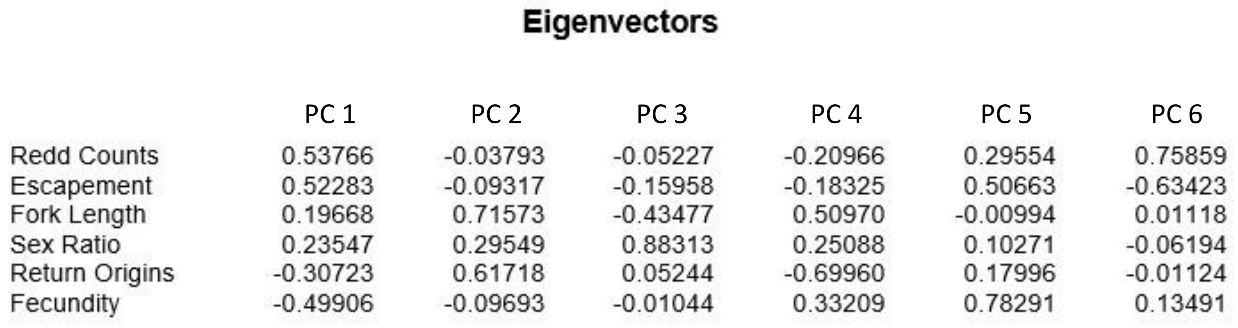
Data analyzed from (Harnish, 2017) (Dauble & Watson, 1990) (Tolson, 2014) (Nugent, 2016) (Brown, 2017) (Brodeur, 2006) (WPSR, 2006) (Smith *et al*., 2015).

Data Analysis: *Principal Component Analysis*

To gain better insight to the relationship between variables, a principal component analysis factored 6 parameters– redd counts, escapement, fork length, sex ratios, return origins, and fecundity– across 15 overlapping years from 2001-2015. The percentage variance explained by the first two principal components was quite high– 55% and 74%, respectively – as shown by the scree plot – suggesting the analysis could partition the data fairly well, with a rapid decline in the percentage of variance explained after the first two components. There was clear clustering of 3 years (2013-15) vs the remaining 12 on the first PC axis.



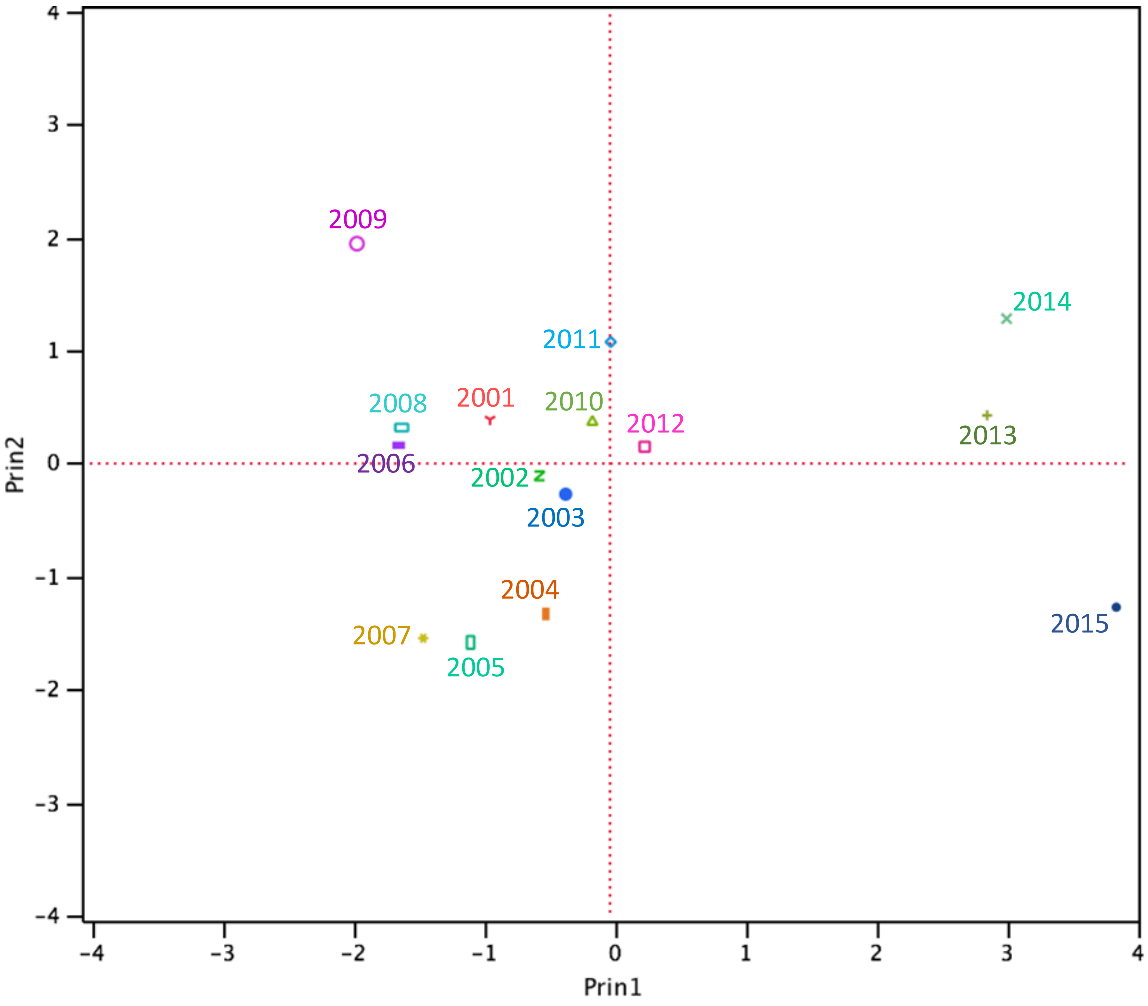
Eigenvectors of the first principal component are weighted heavily and positively toward Redd Counts and Escapement, with an equally heavy negative contribution from Fecundity. The three years 2013-15 are defined by an increase in Escapement, and Redd Counts, and decreasing Fecundity.



Eigenvectors

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Redd Counts	0.53766	-0.03793	-0.05227	-0.20966	0.29554	0.75859
Escapement	0.52283	-0.09317	-0.15958	-0.18325	0.50663	-0.63423
Fork Length	0.19668	0.71573	-0.43477	0.50970	-0.00994	0.01118
Sex Ratio	0.23547	0.29549	0.88313	0.25088	0.10271	-0.06194
Return Origins	-0.30723	0.61718	0.05244	-0.69960	0.17996	-0.01124
Fecundity	-0.49906	-0.09693	-0.01044	0.33209	0.78291	0.13491

This suggests the last three years cluster quite separately from the rest on PC1. PC2 describes increasing fish size (Fork Length), with return origins also increasing in the same direction. Perhaps because larger fish are more likely to be successful in making the journey back to the Hanford Reach to spawn. The years 2004, 2005, and 2007 cluster toward the bottom on the plot, at about the same height as 2015; suggesting that these are smaller fish and there are correspondingly lower return numbers.

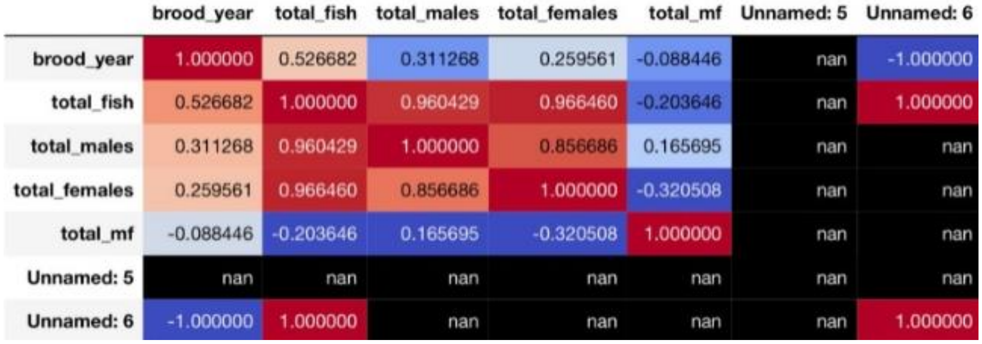


Score Plot

2009
2014
2011
2008
2001
2010
2012
2013
2006
2002
2003
2004
2007
2005
2015
4
3
2
1
0
-1
-2
-3
-4
Prin2
-4
-3
-2
-1
0
1
2
3
4
Prin1

Data Analysis: *Correlation Heatmaps*

After running Seaborn Correlation Heatmaps on all of the raw data I accumulated, the heatmap for Male to Female Ratios by Brood Year indicated a strong correlation. Analysis remains inconclusive, however, as the strong correlation in the heatmap did not bring any new or important associations to light. This was the same data used to create *Figure 6*, which showed a slight female-bias in the wild Chinook population between 1975 and 2015.



	brood_year	total_fish	total_males	total_females	total_mf	Unnamed: 5	Unnamed: 6
brood_year	1.000000	0.526682	0.311268	0.259561	-0.088446	nan	-1.000000
total_fish	0.526682	1.000000	0.960429	0.966460	-0.203646	nan	1.000000
total_males	0.311268	0.960429	1.000000	0.856686	0.165695	nan	nan
total_females	0.259561	0.966460	0.856686	1.000000	-0.320508	nan	nan
total_mf	-0.088446	-0.203646	0.165695	-0.320508	1.000000	nan	nan
Unnamed: 5	nan	nan	nan	nan	nan	nan	nan
Unnamed: 6	-1.000000	1.000000	nan	nan	nan	nan	1.000000

Criticisms of Hanford Science and Analyses

The Hanford Advisory Board (HAB) is a non-partisan and broadly representative body overseeing Hanford cleanup issues. Board members consist of environmental and public health scientists, Tribal leaders, university professors, local governments of surrounding cities, and Hanford workforce members such as union representatives. The primary mission of the Board is to provide scientifically informed and unbiased recommendations to the U.S. Department of Energy (DOE), the U.S Environmental Protection Agency (EPA), and the Washington Department of Ecology (Ecology) on selected major policy issues related to the cleanup of the Hanford Site (Hanford Advisory Board, 2020) (Hanford Advisory Board, 2021). On several occasions, the HAB has expressed disagreement with scientific conclusions or public policy and legal decisions that have been made based on collected data, citing the DOE's issuance of Environmental Impact Statements as "incomplete, inadequate to support proposed decisions, and not prepared in compliance with National Environmental Protection Act (NEPA) processes" (Hanford Advisory Board, 2002) (Reeves, 2000).

After a legal settlement required DOE to prepare Impact Statements (DOE, 2020) the HAB analyzed Statements and found that the DOE did not sufficiently understand impacts of past or continued waste disposal at Hanford, short and long-term impact assessments to ecology, treatment alternatives for radioactive and hazardous constituents and disposal options, and long-term management expectations of the Site. The Statements, representing the federal government's administration of the Hanford Site, excluded "items that needed to be addressed", including lack of legally-required consultation with Tribes or other federal and state agencies, and failure to disclose impacts to groundwater, as well as human and environmental health. "Without explanation, and in apparent violation of applicable standards, the [Statements] provide only a partial description of groundwater impacts for a single well one km away from the burial grounds. Also, failure to include reasonable alternatives to the proposed actions, especially to include an alternative to end the use of unlined soil trenches for disposal. Failure to integrate and consider the cumulative impact of all Hanford waste decisions, the impact of these decisions," and the conclusions the DOE have drawn were contested by the HAB, which called for the Environmental Impact Statements to be rewritten to reflect research results following further analysis (Hanford Advisory Board, 2002) (Reeves, 2000).

Furthermore, the HAB expressed concern over the DOE-suggested twenty-two and twenty-four year delays in waste treatment at Hanford, and the environmental impacts from delayed or incomplete waste handling. Hundreds of pre-1970 tanks sit underground, leaking long-lived, radioactive, and untreated chemical wastes into the soil along the reach of the Columbia River that serves as the world's largest fall Chinook salmon spawning grounds (Hanford Advisory Board, 2007) and "the burial grounds should be addressed. There is inadequate analysis of tank performance. The impacts of hazardous waste buried with various forms of radioactive waste (e.g. lead shielding) should be analyzed, and there is no analysis to support the assertion for the use of deep lined 'megatrenches'… The Board has previously urged that DOE stop disposing of offsite wastes in the low level waste burial grounds until they are fully investigated for disposal of hazardous or dangerous wastes and for releases of hazardous substances (consensus advice #98 and #103). It is vital that the groundwater monitoring around the burial grounds be substantially upgraded. The Board urges the State of Washington to exercise its authority over the burial grounds as dangerous waste management units to meet leachate collection standards, and to prevent the addition of several hundred thousand cubic meters of offsite waste to unlined soil trenches, as proposed in [Environmental Impact Statement]" (Hanford Advisory Board, 2002) (Reeves, 2000) (Hanford Advisory Board, 1999) (Hanford Advisory Board, 2010).

Regarding the environmental impacts of leaking tanks and the need to develop sufficient technology to safely and completely vitrify contaminated waste, the DOE deliberated behind closed doors, excluding regulators, stakeholders, and the public from its review of the technical problems, possible solutions, and possible paths to resolve Hanford site waste disposal, requiring those involved to sign non-disclosure agreements. State and local governments, Tribal leaders, and the HAB asked "DOE to proceed with open and transparent conversations and information sharing with the Board and public. Openness and transparency are essential for public trust, and for good decision-making" (Hanford Advisory Board, 2014) (Leckband, 2011) (Federal Advisory Committee Act, 2007).

Some scientists publishing research on Hanford Reach Chinooks or similar topics that may be directly or tangentially affected by the impacts of Hanford contamination leaks now release a Conflict of Interest Statement with their work. This declaration of competing interest requires the authors to affirm that they "have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper" (Meador *et al*., 2020). Concerning future research and analyses surrounding the continued effects of Hanford chemical and radiation outflows, local and state governments, Tribal councils, Hanford workers and their families, as well as HAB members "urge a more open and transparent process in full accord with President Obama's memorandum to all agency heads on Transparency and Openness, and Freedom of Information; to more effectively involve the regulatory agencies… and the broader stakeholder community in" decisions. "Openness and transparency in the development and discussions of all future actions and plans related to tank waste treatment" and the effects on the surrounding environment are imperative to ensuring the health and safety of humans and the environment in the area (Hudson, 2013).

John R. Brodeur, P.E., L.E.G, an environmental engineer and geologist who formerly worked at the Hanford Site during the 1990s (WPSR, 2006) prepared and released a report criticizing the DOE's "failure to monitor, report, or characterize tank leaks" (Brodeur, 2006). The study characterized suspected new and historical unreported tank leaks of radioactive and toxic chemical wastes (WSPR, 2006) (Brodeur, 2006), which garnered support from public, Tribal, and regional scientific communities. "Brodeur asserts that US DOE's method for detecting tank leaks is not only flawed, but designed to avoid finding leaks. This is based on his own experience at Hanford for many years and was also the conclusion of the Government Accountability Office as early as 1989: 'DOE does not collect sufficient data to adequately trace the migration of the leaks through the soils and studies predicting the eventual environmental impact of tank leaks do not provide convincing support for DOE's conclusion that the environmental impact will be low or non-existent.'" (WPSR, 2006). Additional evidence was presented in Brodeur's paper, also supported by the Hanford Task Force and Washington Physicians for Social Responsibility, of monitoring data reports that identified contamination leaks which were ignored and went unreported by the DOE and its contractors. An institutional bias to avoid detecting, reporting, and addressing suspected leaking tanks and spreading contamination plumes (WPSR, 2006) was also documented by the Government Accountability Office in 1998– the supreme audit institution of the federal government of the United States (GAO, 2020)– stating that the DOE and its contractors, which are still in control of operating and monitoring the Hanford Site as of 2021 (US DOE, 2021), have an inadequate scientific understanding of nuclear waste migration, investigation, and environmental protection at Hanford (GAO, 1998).

Discussion

Most studies and reports reviewed here which specifically assessed the health of salmon in the Hanford Reach of the Columbia River stressed the importance of continued, more detailed, research on wild Hanford Chinooks and their environment. The inconsistencies shown in the results section, of known levels of Hanford Site contaminants coupled with lab-based predictions, as well as evidence and criticisms of intentionally unreported and unmonitored contamination leaks and their effects on the environment, paint a striking contrast against the wild Chinook data published by the DOE and similar. Considering that a large percentage of the adult fall Chinooks returning to spawn in the Hanford Reach are now supplemented by Priest Rapids Hatchery– upriver from the contamination plumes at Hanford– it may be difficult to assess what proportion of wild-origin Chinooks– if any– were or are affected by contaminant upwellings into the Hanford Reach during their early months of development.

Discussion: *Future Research & Analyses*

Openness and transparency regarding the discussions of future Hanford-area monitoring, contamination leaks, cleanup, research plans and findings are all imperative to ensuring environmental health and safety, as well as furthering scientific understanding of the circumstances. Moving forward, studies may do well to test the legitimacy of DOE-collected and DOE-funded datasets in meta-analyses. Additionally, ambiguity and unreliability in many existing forms of data surrounding Hanford Chinook could potentially be solved by conducting genetic studies where there would be less room for vagueness in the results. Epigenetic impacts of a something like a Ryman-Laikre effect or potential stress-induced TEs interacting between hatchery a wild populations would be a great place to start. The answers to those questions may provide a jumping off point for more analyses also offer a more complex but complete explanation for what is happening with Hanford Chinooks and their environment.

Over the past eight decades, very few studies have attempted to examine the long-term or indirect effects of chemical exposure, especially on a genetic level. Also, the few studies which have tried to run controlled lab simulations exposing Chinooks to known Hanford Site contaminants in the levels actually found at the Site have produced more concerning results than the *in situ* DOE-funded studies that tend to conclude “everything seems fine”. More importantly, there have been no multifactorial studies considering the interacting effects on varied levels of Hanford Site pollutants and chemicals, in addition to background radiation. A holistic, integrated, multidisciplinary approach to future Hanford research may allow for bigger picture understanding moving forward. For example, hatchery-originated Chinooks now make up 93% of the wild spawning population, and annual redd counts overall seem to be increasing. Big picture, however, there is an overall reported decline in health of both wild and hatchery fish all along Pacific coast, with adults returning to spawn younger and younger, lowering fecundity. It is unknown why such a large percentage of returns are of hatchery origin when most Hanford monitoring reports suggest the Hanford Reach is safe and the wild fish are healthy. Taking extra care and concern to ensure the health of this population can be justified, considering that the Hanford Reach is the most productive remaining naturally-spawning Chinook habitat on earth, and less than 7% of returns are comprised of wild fish.

Conclusion

Care must be taken to protect and enhance the most productive remaining naturally-spawning population of fall Chinook salmon. Pollution and widespread habitat destruction in other areas of the Columbia River have increased the importance of the Hanford Reach to maintaining Chinook populations worldwide. While extensive hatchery supplementation has allowed the salmon runs to continue, it should not be assumed that these returns can be maintained indefinitely with the current management strategies. Hatchery-origin Chinooks already have lower fecundity and more unbalanced sex ratios; and these fish comprise up to 93% of the fall salmon runs returning to spawn in the Reach. With continued unbiased research and monitoring, current and future contamination leaks could be identified and mitigated, limiting harm to the vulnerable Hanford Reach Chinook population.

Lab and *in situ* experiments indicate that Hanford Chinook spawning habitat is both diminished and threatened by the contamination plumes leaking from the Hanford Site. While there are many DOE and similar annual reports suggesting surface-level stability of the situation, there are enough contradictory reports- such as 84% of wild female Chinooks turning out to be genetically male- that have never been followed up on, reproduced, extrapolated on, or seemingly taken seriously. Beginning epigenetic research on Hanford Chinooks could bring the fight to save or at least preserve this population into the twenty-first century. The Hanford Reach spawning area and fall Chinook population are classified as

Level 5 resources, the “highest ranking, rarest, and most sensitive habitats and species… considered irreplaceable or at risk of extirpation or extinction” (Nugent, 2016) (Dauble & Watson, 1997). This population and their spawning habitat are of significant interest to federal, state, and Tribal governments, as well as the public; as these fall Chinook salmon have been vital in efforts to preserve and restore other depleted Chinook salmon stocks in the Columbia Basin and beyond.

Acknowledgements

Space does not permit me to thank all of the wonderful people who have shared their data, time, support, and ideas with me over the past seven months of working on this project. Additionally, due to the sensitivity of some data, many important contributors would prefer that their names not be put in print. I would, however, like to thank Nord University’s endlessly patient and encouraging FBA, my supervisor Dr. Les Noble who is full of both wisdom and sayings such as “There’s a bee in my bonnet”, and Joshua James Kelly O’Connor for all things technological and emotional support.

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