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SALMON EXPOSURE TO CHROMIUM IN THE HANFORD REACH OF THE COLUMBIA RIVER: POTENTIAL EFFECTS ON LIFE HISTORY AND POPULATION BIOLOGY

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Executive Summary

Salmon are an important economic, ecologic, cultural and Tribal resource in the Pacific Northwest, including the "Hanford Reach" of the Columbia River where it flows along the Department of Energy (DOE)'s Hanford Site. Among the 40+ species of fish, and several species and genetic stocks of salmon, the fall-run Chinook Salmon (*Oncorhynchus tshawytscha*) is probably of the greatest importance to the Reach and the Columbia Basin. A significant portion of the Fall Chinook Salmon construct their nests (redds) in the Hanford Reach, with a large concentration near Locke Island and thus alongside reactor areas 100-D through 100-F. Several regulatory and remediation decisions for the Columbia River Corridor are based on protection of the aquatic resources of the Columbia River from contamination and depletion, including issues dealing with the potential harm to salmon populations. The primary contaminant of concern for this report is hexavalent chromium (also designated Cr-VI or Cr^{6+}).

In this report we address life history and habitat requirements of salmon generally and of different species of salmon, population levels and trends of Fall Chinook Salmon, overall factors affecting population levels of Fall Chinook Salmon in the Columbia River, and the potential for toxic effects of chromium on salmon and salmon populations. Our overall objectives are to understand whether and how chromium contamination in groundwater plumes and upwellings enter the river, and how they might currently and potentially in the future, affect the behavior, survival, and population levels of salmon in the Columbia River. We examine the potential implications of chromium toxicity, among other factors, for remediation and restoration of salmon populations. Information is generally available for Fall Chinook Salmon, but not necessarily for Fall Chinook Salmon specifically from the Columbia River adjacent to the Hanford Site.

Regardless of the regulatory framework and scientific information available, some people believe that "some of the salmon spawning areas at Hanford are significantly contaminated by chromium" (Columbia Riverkeeper 2013), while others disagree (Dauble et al. 2003b). Washington State Department of Ecology stated that "research to date shows no negative impact to salmon from chromium concentrations" in the Columbia River (Washington Department of Ecology, http://www.ecy.wa.gov/programs/nwp/salmon.html).

Chinook Salmon, a species of special concern to the Tribes and others, have a complicated life cycle. They spend 1-3 years in the Columbia River and its tributaries, and up to 8 years at sea. Fall Chinook Salmon spawn in the Columbia River itself, while juvenile and adult spring and summer Chinook Salmon pass through the Hanford Reach en route to other rivers or tributaries. The life stages include eggs laid in redds, alevin that remain in the gravel

for weeks, fry after "swim-up", parr, and smolt that spend months in freshwater in the early stages. After spawning, eggs imbibe water and harden. Eggs take three months to hatch. Alevins (recently-hatched fish) remain in the gravel in redds for several weeks, while absorbing their yolk sacs. The median time from the eyed egg stage to swim-up is 83 days (Dauble et al. 2003b). Fry are young fish that have just emerged ("swim-up") from the redds. Parr are older fish that have developed camouflaged striping and remain in this stage for several months. Parr metamorphose to smolt, the stages that swims downriver to the estuaries. Adult salmon spend 1-8 years at sea before returning to natal rivers and streams to spawn.

The key aspects of their life history that make them potentially vulnerable to chemicals (including chromium) are the time spent as eggs, embryo and alevin in redds in gravel (exposed to groundwater upwellings), and the time spent as fry or parr in nearshore areas where they might be exposed to chemicals in the food chain if they remain within a small area. The spatial distribution of redds and their possible exposure to chromium-containing upwellings varies from year to year.

Key habitat requirements for redds include characteristics about: a) water flow (velocity about 0.23-2.25 m/sec, with few fluctuations) that ensures oxygenation (9 mg/L) of the eggs, b) grain size (gravel, 25 to 305 mm, with little fine sediment), and c) a water depth of 0.3 to 9.5 m. The conditions are ideal along parts of the Hanford Reach, which once accounted for up to 90% of the spawning in the central-Columbia River Basin, although recent data indicate that the proportion in the Reach is declining due to increases elsewhere (Mueller and Ward 2010). Flow characteristics are a function of natural conditions (snowmelt, rainfall throughout the watershed) and water management practices (releases) at the upriver dams (primarily Priest Rapids Dam), making it essential to understand both the needs of developing eggs and alevins (that remain in the gravel), and the timing of life-cycle events (how many weeks or months eggs or alevins are in the gravel), as well as the mobility and habitat selection of young fry and parr that may be exposed to chromium through the food chain.

Population levels of spawning Fall Chinook Salmon in the Columbia River were low and remained relatively stable when data were first collected in the 1940s into the 1970s. The low population was attributed to impassable dams and extensive harvesting, with fewer than 20% of adults escaping these hazards to reach their spawning grounds. With improved management of fisheries and hydroelectric facilities, numbers of spawning adults began to increase in the 1970s, reaching a peak in 1987, and then have continued cycling up and down to the present. While management (decreased harvesting, improved fish passage and better water release practices) may have resulted in increases in spawning salmon in the Hanford Reach – the increase may also have been due to effects of upriver dams (e.g. changing operations or fish ladder construction at Priest Rapids and on the Snake River), resulting in spawning in the Hanford Reach.

Factors that affect population levels vary among salmon species, and include genetics, life histories, population dynamics, habitats, human history and influences, hydroelectric systems and mitigation, artificial production (hatcheries), harvest management in estuarine and marine environments, conservation, pollution, predation, and environmental remediation. The major adverse effects on salmon populations are from harvests and from hydroelectric dams. The dams interfere with adult salmon spawning runs and impede downriver movement of juveniles; dams also control water releases during spawning periods. In addition a hatchery production may be endangering the genetic integrity of native stocks, and shoreline land development impacts water quality. Salmon populations are regulated and managed by natural resource trustees, including federal, state, and Tribal governments. Salmon are critical for Native American cultures that have been in the Columbia River area for more than 9,000 years (Harris and Harper 2004, Lambert 2008).

Salmon biologists (as indicated by several books and hundreds of papers) would concur that "pollutants …generally are not considered a major factor in salmonid declines, nor are they particularly problematic for recovery" (Stanford 2006, p 211). The U.S. Environmental Protection Agency's (EPA) report on toxics in the Columbia River Basin (EPA 2009) did not even mention chromium. Lambert's (2008) tribal perspective emphasized DDT and PCBs, in salmon, but not chromium. However, some DOE site managers, some regulators and Tribal governments, are concerned about the potential effects of hexavalent chromium, which is known to have both acute and chronic effects on invertebrates and fish, varying by age, species, experimental conditions, and water hardness.

For many years hexavalent chromium was used abundantly in reactor cooling water at the Hanford Site to prevent corrosion, and until 1971, through water management practices and unplanned releases, large quantities of hexavalent chromium were discharged to the soil, seepage basins, cribs and River. Subsequent discharges were less direct, but contributed to major sources with ongoing release to groundwater at several of the Hanford reactor sites. Chromium in plumes is now moving slowly toward the river, and is entering the river through underground pathways and emerging as springs, seeps, and upwellings in the river bed. Extensive groundwater pump and treat and soil excavation cleanup activities have been carried out to intercept the plumes and mitigate chromium contamination of the River

There have been many studies of chromium toxicity in fish, mostly with high level acute exposures. Some studies have been conducted on salmon. Dauble et al. (2003b) summarized information on the adverse effects of chromium on Fall Chinook Salmon. We briefly summarize the literature on chromium toxicity to fish, and we examine three relevant well-controlled studies in detail. Most laboratory studies examined acute effects over a matter of hours or days, but the relevant studies for this report are those that examine chronic effects from low level exposure over weeks and months. No effects on salmon were found in Hanford-relevant chromium exposures up to 266 μg/L for fertilization or hatching (Farag et al. 2000, 2006a; USGS), or for survival of alevins that do not eat, but remain in the gravel (Patton et al. 2007; Neitzel et al. 2005; Duncan et al. 2007). Thus 266 μg/L can be considered a no adverse effects level or concentration (NOAEL or NOEC) for Chinook eggs and alevin survival (Patton et al. 2007).

However, Farag et al. (2006b) found increased mortality, decreased growth, lipid peroxidation indicative of oxidative stress, metabolic changes, and kidney damage when 60 day post-swim-up fry (parr stage) were exposed to 54 μg/L for 105 days followed by 266 μg/L for 29 days. Some effects were also seen in fish exposed to 24 μg/L for 105 days followed by 120 μg/L for 29 days. Farag et al. (2006b) also reported DNA changes of uncertain significance after 105 days at 24 μg/L. The change in concentration after 105 days makes it difficult to identify specific toxic concentrations. Since this sensitive stage occurs mainly in the River, where chromium concentrations are mainly below detection levels (typically less than 5 μg/L), we conclude that chromium is not likely to have significant impacts on populations of salmon fry, because: 1) after swim-up the vulnerable fry are no longer in gravel (thus, no longer exposed to pore water that can have high chromium levels), 2) fry feed on invertebrates (mainly insect larvae), and therefore are exposed to chromium at river food-chain concentrations rather than upwelling and pore water concentrations, and 3) chromium concentrations in Columbia River water are below detection or practical quantification levels.

Chromium levels in fry and parr should be examined to determine if there are food chain effects. The fry stage is highly vulnerable. The fry begin to feed independently and experience high mortality due to natural causes (Farag et al. 2000). The likely phenomenon of fry being swept downriver by strong currents once they emerge from redds, and the possibility that some may end up in shallow side areas with little water movement and upwellings, hiding close to the substrate, should also be further examined.

The chromium concentration of pore water is considered the most relevant medium to examine for any possible effects on salmon because the early life stages (eggs and alevins) live in the spaces among the gravel for a period of 3-4 months, and they remain in one place. Pore water is directly affected by groundwater. Levels of chromium in the pore water within the river bed along the 100 Area of the Hanford Site average less than 23 µg/L although they range as high as 632 µg/L. About half of the pore water samples (n= 355) had detectable chromium (above the practical quantification level of 3.7 µg/L. About 25% have levels above 10 µg/L and 1% had levels above the NOAEL of 266 µg/L for eggs and alevins. For Chinook Salmon, fry or parr (juveniles that have emerged from the gravel) are more sensitive to chromium than eggs or alevins. Data on hexavalent chromium concentrations in aquatic invertebrate tissue would facilitate evaluating food chain effects. Thus, any conclusions about food chain effects are dependent upon results from further study which is needed.

The current Washington State Ambient Surface Water Criteria for chronic exposure to hexavalent chromium is 10 µg/L, while the Environmental Protection Agency (EPA) chronic ambient water quality criterion for chromium is 11 µg/L. The standard applies equally to total chromium and hexavalent chromium (Cr-VI; see below). The Washington State Ambient Surface Water Criteria, which DOE considers an Applicable or Relevant and Appropriate Requirements (ARAR), was developed from a set of bioindicator assays, which are representative of freshwater species, but are not necessarily those species present in any given river (e.g., Columbia River). The Washington Department of Ecology's current position is that "Research to date shows no negative impact to salmon from chromium concentrations," and conclusions from ecotoxicologic studies concur that the value of 10 µg/L (Farag et al., 2006a,b; Patton et al. 2007) would be protective of salmon, both directly and indirectly by protecting the food chain on which the juvenile salmon depend. However, the concentration of 10 µg/L may also be considered overly conservative for pore water, in contrast to the no observed effects level of 266 µg/L for eggs and alevins (Farag et al. 2006a, Patton et al. 2007), which is relevant to the upwellings.

The data and information provided in this report can be used in a risk evaluation, where sources of chromium may be linked through subsurface transport (fate and effects) to salmonids in the Columbia River. In this report we mainly concentrated on Fall Chinook Salmon, although information on other species is given where relevant. We conclude that:

1) Salmon are important cultural, economic, and symbolic species within the Columbia River Ecosystem, particularly for Native Americans and other Pacific Northwesterners. Some tribes consider them a critical cultural element;

2) Several species of salmon spend a significant part of their life cycle in the Columbia River (environmental factors are expected to act similarly on all the salmon);

3) Salmon populations, particularly Fall Chinook Salmon, have increased in the Hanford River, and the number of redds (nests) has increased dramatically in the Hanford Reach since the 1970s;

4) Up to 90% of the Fall Chinook Salmon spawning in the central Columbia River did so in the Hanford Reach until recently when numbers in the Snake River also increased;

5) The primary factors affecting population levels of salmon in the Columbia River are commercial and recreational harvesting, hydroelectric power preventing upriver and downriver migration and controlling water flow (and levels), and hatchery production, although industrial, mining, agricultural and residential development also impact the Columbia River ecosystem (and thus habitat for salmon);

6) Contaminants (such as chromium) are not viewed to be of major concern by most technical fisheries experts, who focus on dams, river flow, catch rates, and other issues;

7) Chromium, including hexavalent chromium, is one of the contaminants of concern for the DOE and the Hanford Advisory Board (River and Plateau Subcommittee, HAB webcast, January 2012), and has been stated as the driver for clean-up in the Columbia River corridor by some DOE officials;

8) In a summary and synthesis of the effects of chromium on fish (free swimming), Eisler (1986) reported that "adverse effects of chromium to sensitive species have been documented at 10 µg/L [hexavalent chromium] in freshwater"; sensitive species are largely invertebrates (not salmon). Uptake and/or toxicity of chromium are influenced by pH and are greater at low water hardness;

9) Laboratory and *in-situ* field experiments on the effects of chromium on fish indicate that there is a great deal of variability in results, depending upon fish species, age, chromium species used, exposure method, and effects reported;

10) No effects were found in Hanford-relevant chromium exposures for salmon fertilization, hatching, and exposure of alevins (that do not eat but remain in the gravel) (Farag et al. 2006a; Patton et al. 2007),

11) Farag et al (2006b) found increased mortality, decreased growth, lipid peroxidation metabolic changes and kidney damage when parr were exposed to levels of 54 µg/L for 105 days followed by 266 µg/L for 29 days (54/266 group). Adverse effects were subtle after 105 days, and were pronounced after 134 days. Some significant effects were seen in the fish exposed at 24 µg/L for 105 days followed by 120 µg/L for 29 days (24/120 group). However, parr in the Hanford Reach probably are not exposed to significant concentrations of chromium in river water (e.g., chromium levels in river water are predominately below detection levels).

12) The no observed effect concentration (NOEC) for Chinook from the Columbia River for eggs and alevins is 266 µg/L (present in the redds with potential exposure to groundwater upwellings containing elevated chromium concentrations). Effects levels have been observed for parr at 54 to 120 µg/L. DNA changes of uncertain consequence were reported at 24 µg/L for 105 days. After swim-up fry may be vulnerable if they linger near the gravel surface where they might be exposed to the interface of pore water and river water.

We recognize that there are regulatory requirements for reducing and monitoring chromium contamination in groundwater and surface water of the Columbia River Basin that go beyond the health of salmon populations. Overall, it is unlikely that hexavalent chromium in the groundwater, pore water and Columbia River that originates from the Hanford Site is having an adverse effect on population levels of Fall Chinook Salmon, under the present conditions (e.g. pump and treat, no additional sources or new preferred pathways). The current role of exposure to hexavalent chromium on Chinook Salmon populations in the Columbia River (and the Hanford Reach) is very minor and likely insignificant compared to the other stressors on salmon population, including dams (that impede movement to natal spawning areas, downstream movement of juveniles, and change river flow and volume), fisheries (that remove reproductive adults), hatchery production (that dilute native stock), predators on juveniles in the estuary (by terns, cormorants and sea lions (Marshall 2012), competition for food in the ocean, urban and other sources of nutrients, and toxics (e.g., metals from mining). We did not address chromium effects on benthic organisms, which if significant, could pose a problem for salmon. In our estimation, given the toxicity data, effects levels, the magnitude of effects, and the current levels of chromium in pore water (that could directly affect eggs and alevins) and in the Columbia River water (that could affect fry, parr, and adults), there are likely no current or foreseeable measurable effects of chromium from the Hanford Site on salmon populations in the River.

We thank the many reviewers who commented on the Factual Review draft of this report and made valuable suggestions (sometimes contradictory ones). We paid attention to and responded to all. We corrected errors, and incorporated as many suggestions as were feasible. This document is broad in scope and deals with complex issues. This report is not intended to be a risk assessment nor does it deal with resource damage assessment, remediation options, or future land uses, all of which are of vital interest to many stakeholders.

Table of Contents

The overall objective of this document is to examine the potential impact of chromium derived from the DOE's Hanford Site on salmon, particularly Fall Chinook Salmon in the Columbia River. We examine life history and life cycles of salmon, temporal and spatial patterns of spawning, environmental requirements for redds (nests), population levels of spawning adults and counts of redds, factors affecting salmon populations, laboratory and field studies of the toxic effects of chromium on salmon, potential consequences, and management implications of the aforementioned factors. General life history, spawning behavior and habitat selection information on Chinook Salmon are central to understanding the potential for exposure to a range of stressors, including contaminants, hydroelectric dams, water flow variations, and variation in snowmelt and rainfall, as well as other stressors. An important assumption of this report is that any potential effects of chromium on salmon occur within the context of both the life history and behavior of salmon, and the complex of the physical environment and stressors that salmon face.

Introduction

Salmon are an important resource in the Pacific Northwest, including the Hanford Reach where the Columbia River flows along the DOE's Hanford Site. Salmon are keystone species in the river ecosystem, iconic and symbolic, and are important bioindicators because of their Tribal, cultural and economic importance to the Pacific Northwest (NRC 1996, Landeen and Pinkham 1999, Dauble 2009), and also because of their varied genetic diversity, life cycle diversity, and varied habitat requirements (Williams 2006, Burger et al. 2013). Salmon are anadromous, laying their eggs in freshwater, migrating to the sea as juveniles or adults, and returning years later as mature adults to spawn in their natal habitat. For most salmon species adults spawn only once, and then die.

There are several species, and many genetically distinct "stocks," of salmon in the Pacific Northwest, and there is still controversy about the taxonomy and the varied genetic lineages of each species (Narum et al. 2010). Salmon are heavily fished both recreationally and commercially, as well as being culturally important to Native Americans (CRITFC 2013). In the Columbia River, there are five species of salmon (EPA 2009), and although this document focuses on Chinook Salmon (*Oncorhynchus tshawytscha*; also known as King Salmon), the others are important, and toxicological data are presented when available for any of the salmon species, including the Rainbow Trout (better known in Washington as Steelhead, *Oncorhynchus mykiss*). The Rainbow Trout is widely used in aquatic toxicology research, and is usually identified in pre-1989 literature as *Salmo gairdneri*, while *O. mykiss* is the currently accepted name. Most available published information is about Fall Chinook Salmon, rather than on those that spawn in the spring. Fall Chinook Salmon spawn in the Columbia River itself, while adult spring and summer-run Chinook Salmon pass through the Hanford Reach en route to other rivers or tributaries (DOE/RL-2000-27). All species, and all runs, are important to Tribes (R. Buck, pers. comm.), and the spring Chinook run is especially important to the Nez Perce (G. Bohnee, pers. comm.). Several of these salmon populations or lineages (e.g., Spring-run Chinook, Steelhead) are listed as threatened or endangered (Bottom 2005, FWS 2012).

Adult Chinook include an endangered spring run and summer run, and the large, non-endangered fall run which spawns in the autumn. We focus on Chinook Salmon because it is the species most often studied in the Hanford Reach and vicinity. The fall run of Chinook Salmon (Fall Chinook Salmon) is abundant, extensively fished by recreational and Tribal fisherman, and is of cultural interest to the local Tribes and Pacific Northwesterners. The Hanford Reach (the section of the Columbia River adjacent to the DOE's Hanford Site), is one of the most significant mainstem spawning habitats for fall Chinook Salmon (OHWB 2002). Historically, Fall Chinook Salmon spawned over a 900 km distance of the Columbia River, but they were largely restricted to a 90 km section of the Hanford Reach because of dams (Dauble and Watson 1997, Dauble 2009). They are now increasing, particularly in the Snake River (Mueller and Coleman 2008, Mueller and Ward 2010). There is great variability in the proportion of adult Fall Chinook Salmon passing the McNary dam and escapement to move into the Hanford Reach, Priest Rapids pool, and the Snake River, particularly since the mid-2000s (Mueller and Ward, 2010).

The issue of salmon conservation in the Pacific Northwest is complicated by the hydroelectric system of dams (Dauble 2000, Dauble et al. 2003a, Levin and Tolimieri 2001), by harvest limits (Hyun et al. 2012b), and the large-scale supplementation of populations with hatchery fish (Holsman et al. 2012, Kostow 2012). Harvests of Chinook salmon were as high as 19.5 million kg in 1889 from the Columbia River system, but by 1960 the harvest had declined to less than 5 million kg (Fulton 1968, Chapman 1986). Harvest numbers do not necessarily represent population numbers, but usually reflect either harvest limits imposed because of declining fish populations, or the inability of fishermen to find salmon at low density (even with new fish-finding technology). After the Boldt decision, which affirmed tribal rights to 50% of the salmon harvested from the river, salmon populations began to increase, partly as a result of a more holistic approach to management (R. Jim, pers. comm.), considering a broader range of issues.

Dams are not only an obstacle to fish movement, but the water release regime at a dam can rapidly change the water flow and level downstream of the dam. During the incubation and hatching period for salmon eggs, low water or dewatering events can leave redds exposed or can strand juvenile fish in tiny pools. Major dewatering events in the 1970s resulted in heavy juvenile mortality. A major decision impacting salmon populations is the Vernita Bar Agreement (1988 and amendment in 2004), which addresses the flow fluctuations in the Hanford Reach to reduce impacts on salmon redds and juveniles. The Agreement among agencies representing fisheries, hydropower, flood control and irrigation, requires dams to maintain adequate water during incubation and hatching and reduced water level fluctuations during the critical periods from spawning to hatching (Coutant et al. 2006).

An additional issue is the role of hatcheries which rely on harvesting a significant number of returning adults. More importantly, hatcheries produce more offspring that reach adulthood than wild salmon in the same rivers (Hess et al. 2012). Priest Rapids Hatchery releases several million juvenile salmon each year into the Columbia River (Lewis and Pearson 2012). Hatchery fish, however, seldom have as high adult survival rates as indigenous fish (Stanford et al. 2006, R. Buck, pers. comm). This may change, however, as Tribal fish hatcheries mimic more natural conditions by providing higher flow, elevation gradients, and exposure to predators (Nez Perce hatcheries, G. Bohnee, pers. comm.). Hatcheries also trap a significant number of wild adult salmon for "captive" breeding (Lewis and Pearson 2012).

One widely and strongly held conclusion among technical analysts and tribal observers alike, is that the river should be returned to conditions of natural water flows, intact littoral habitats, and biotic and human communities (Williams et al. 1999). However, Hobbs et al. (2013) caution that given global and demographic changes, it is unrealistic to assume that any ecosystem, much less one experiencing ongoing energy, mining, agricultural, and industrial impacts, can be restored to pristine conditions. Nonetheless, natural water flow and native habitats, can be restored even if it is not possible to return the River basin to historic "natural conditions".

Salmon declines have resulted in cultural deprivation for some Native American tribes that have been using salmon from the Columbia River Basin for over 9,000 years (Landeen and Pinkham 1999; Butler and O'Connor 2004, Lambert 2008, CRITFC 2013). Even when populations were low, salmon was a major food item for native peoples, and migratory salmon had well-established spawning populations in the Columbia Basin (Butler and O'Connor 2004). Maintaining healthy salmon populations is a local, regional, and national goal (NRC 1996).

Since the DOE's Hanford Site borders the Columbia River, there is concern that radionuclides and other contaminants entering the river are impacting salmon and the Columbia Basin ecosystem generally. The Hanford Site (586 square miles) was developed during World War II to produce plutonium for the atomic bomb. It subsequently played a major role in the US nuclear program, including operation of nine reactors which depended on the Columbia River for cooling water. For many years hexavalent chromium was used in reactor cooling water at the Hanford Site to prevent corrosion, and until 1971, large quantities of hexavalent chromium were discharged directly into seepage basins, and then flowed into the groundwater. Subsequent discharges were less direct, but contributed to major sources with ongoing release to groundwater at several of Hanford's reactor sites. Chromium in groundwater plumes is moving slowly toward the river, and entering the river through underground pathways and emerging as springs, seeps, and upwellings. Extensive excavation of contaminated soil to remove the source of chromium has occurred, and a groundwater pump and treat system has been installed with the intent to mitigate the transport of chromium to the Columbia River (Truex et al. 2012, Neshem et al. 2014).

The EPA wrote a *State of the River Report for Toxics* in 2009, listing the contaminants of concern for the Columbia River as mercury, DDT (and its breakdown products), PCBs, and PBDE flame retardants (EPA 2009). While some members of Tribes worry about contamination from radionuclides and chromium, there is also growing concern about other chemicals to which salmon are exposed while in the ocean, including possible contamination from the Fukishima nuclear disaster (e.g. Nez Perce, Wanapum, pers. comm.). By contrast, the Columbia Riverkeeper considers the major contaminants of concern at Hanford to be hexavalent chromium, followed by strontium-90, tritium, uranium, carbon tetrachloride, and iodine-129.

Columbia River Basin Salmon

The Columbia River Basin (Fig. 1) once had the largest salmon runs in the world (10-16 million fish), but these decreased to about a million upriver salmon (EPA 2009) and then increased subsequently (Columbia Riverkeeper 2013b). The Hanford Reach, along the DOE's Hanford Site, is the largest mainstem stronghold for all Chinook. Until recently, it supported up to 90% of the fall Chinook that return to the central Columbia River (Dauble et al. 2003a, Williams et al. 2006), although the number of fall Chinook Salmon are increasing in the Snake River.

Different segments of the Chinook population run up river in spring, summer, and fall. The much smaller spring and summer runs are considered endangered (Chelan, 2012). The difficulty is that all (or part) of each run occurs in different tributaries and sections of the main Columbia River.

Salmon runs on the Columbia River have been severely impacted by dams (Figure 1) that impede access to their traditional upstream spawning areas (Hanrahan et al. 2004), and a significant proportion of fish fallback when attempting to overcome obstacles when moving upstream (Boggs et al. 2004). Dam improvements may have lessened this impact somewhat (Mueller et al. 2012). Determining the rate of fallback, and of re-ascension is difficult, and is being pursued with use of marked (PIT tags, radiotelemetry) fish of different ages, examined at different dams (Mueller et al. 2012; Boggs et al. 2004). Ascension rates vary by dams for adult Fall Chinook Salmon (Ice Harbor dam = 1.7 %, McNary Dam = 0.8 %, Priest Rapids dam = 5.6 %; Mueller et al. 2012). Radiotelemetry can also be used to examine passage times through fishways (Bjornn et al. 1996). Additionally, some juvenile fish migrating downriver are killed in the turbines. Although these issues were more severe in the past (Dauble et al. 2003a), they still are present.

Dam construction on the Columbia River began in the 1930s with Rock Island and Bonneville Dams. Flows through the Hanford Reach are primarily controlled by Grand Coulee Dam in the U.S. (built in 1942), and Mica and Keenleyside Dams in Canada. Priest Rapids Dam operates as a run-of-the-river dam, rather than a storage dam, but its release practices control flow in the Hanford Reach (Neitzel et al. 2005).

The Pacific Northwest is embroiled in major public policy debates about how to restore Pacific salmon. Because of its importance to Native American Tribes in the area, to commercial and recreational fishermen, and to ecosystem integrity in the Columbia River (as well as elsewhere in the northwestern U.S.), it is critical to consider ways to assess salmon population health and stability. In this document we use Fall Chinook Salmon, the most abundant species of salmon in the Basin (Fulton 1968) as a bioindicator, although information on other species is presented where informative.

Salmon runs in the Columbia River, Snake River, and Yakima River and their tributaries are complex and changing (Mueller and Coleman 2008, Mueller and Ward 2010). In general, Fall Chinook Salmon spawn in the mainstem Columbia River, and spring/summer Chinook Salmon spawn in the Snake and Yakima Rivers and small tributaries. Throughout this document general information about salmon and the threats they face relate to all Chinook, as well as other salmon. Even much of the spawning information relates generally to Chinook, but our emphasis is on Fall Chinook Salmon because they spawn in the Columbia River adjacent to Hanford, and have been the subject of toxicology research with hexavalent chromium.

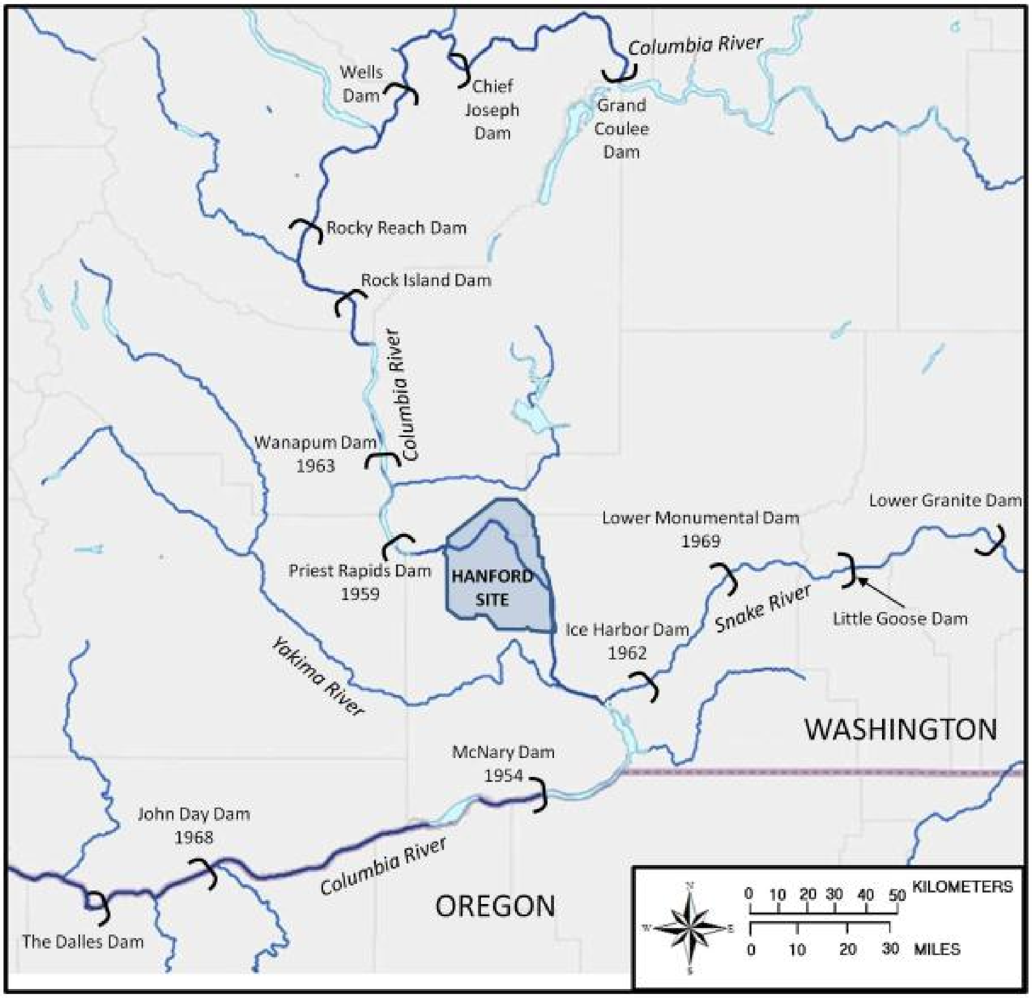

Fig. 1. Map of the Columbia and Snake River showing dams. The construction dates of the major dams affecting the Hanford Reach, and the confluences of the two rivers with the Columbia, are also shown. Dam construction began in the 1930s (Rock Island, Bonneville). Priest Rapids Dam is upriver and McNary Dam is downriver of the Hanford Site.

Life History, Habitat Requirements and Vulnerability to Contaminants

Salmon eggs are laid and hatch in freshwater gravels. The young spend a variable part of their lives (months to years) in freshwater and thereafter swim to the ocean, where they grow and mature over a period of years (1-8 years, Johnson et al. 2012, Sharma and Quinn 2012). General life history information for several species of salmon is shown in Appendix A. Fall Chinook Salmon spawn in the Columbia River itself; spring and summer Chinook Salmon pass through the Hanford Reach en route to other rivers or tributaries. A few Chinook Salmon spend their entire lives in freshwater (Connor et al. 2005, Johnson et al. 2012). Adults come back to their natal river to spawn (and die there). When adult salmon come upstream, they must pass several dams to reach spawning areas. There they dig or excavate nests (located in spawning areas called redds) in the gravelly substrate. Eggs are buried (relative to the elevation of the original bed surface) from 5.5 to 51.5 cm, with a mean of 22.5 cm to the top of the egg pocket and 30 cm to the bottom of the egg pocket (Evenson et al. 2001). Those that hatch in the river itself typically spend less than a year in freshwater before migrating to the sea (Chelan 2012), and Dauble and Geist (2000) estimated that they normally reach the ocean within 3 months of emergence from the spawning substrate. Some salmon are capable of swimming the 2,600 river km from Idaho to the Columbia River and back within 4 months (Johnson et al. 2012).

Life history strategies differ in Chinook Salmon (Fig. 2). Males, for example, represent a continuum of the different strategies (Johnson et al. 2012). Males may mature a year earlier than the females from the same cohort (i.e. precocious maturation). Determining the maximum times in each stage and location (upstream, river, estuary, ocean), however, is difficult. For example, water and oxygen conditions can affect egg development.

As a further complication, there are two life history strategies that occur in the Columbia River – precocial males that spend their first year in the ocean and then return to breed (called jacks), and fish that generally migrate to the ocean during their first year and spend several years there. A few remain in freshwater and do not migrate to the ocean (Sharma and Quinn 2012). Jacks winter in the ocean and return relatively quickly to breed in natal streams. Further, some salmon spend their whole lives in freshwater, never entering the ocean, but return farther upriver to spawn. Vulnerability of each life stage depends on the timing and duration of a given stage. The length of the spawning period determines the length of the period that egg-stage salmon are vulnerable to environmental conditions (e.g. water flow, oxygen, contaminants; see below). The life cycle patterns for Chinook Salmon are given in Figure 2.

From Figure 2 it is clear that one critical phase in the life cycle occurs when eggs and alevin are in the gravel because they are place-based, and dependent upon the conditions at the nest site (called redds). It is here that environmental conditions can play a key role in survival of eggs and alevins (recently hatched young that remain in the gravel), and where contaminants have the potential to affect eggs and alevins because they are exposed to pore water which is locally fed by groundwater upwellings. Eggs in the redds can be exposed to these contaminants through movement across the egg membrane, particularly before hardening. Figure 3 below shows the relationship between redd location and physical features.

Figure 3 illustrates that redds are in contact with pore water, in the hyporheic zone where well-oxygenated river water contacts the pore water (Bunn et al. 2012). There must be suitable water flow to provide sufficient oxygen through diffusion and pore water irrigation. On the other hand, redds cannot be in water with a very high velocity that would dislodge eggs from redds. Selection of nest pockets within spawning areas (redds) is critical to reproductive success, and spawning habitat is limited by deep water and low water velocity (Hanrahan et al. 2004, 2005). Important substrate characteristics are pebble size (pebbles or stones allow for water movement), grain size in the nesting area, water depth, and water velocity. While spawning areas will change as a function of these characteristics (discussed in more detail below and in Appendix A), the primary spawning areas for Fall Chinook Salmon in the Columbia River occur along the Hanford Reach, as well as below the Priest Rapids Dam and in the Snake River (Fig. 4). The data for this figure are available in geographic information system (GIS) format (K. Brown, pers. comm.).

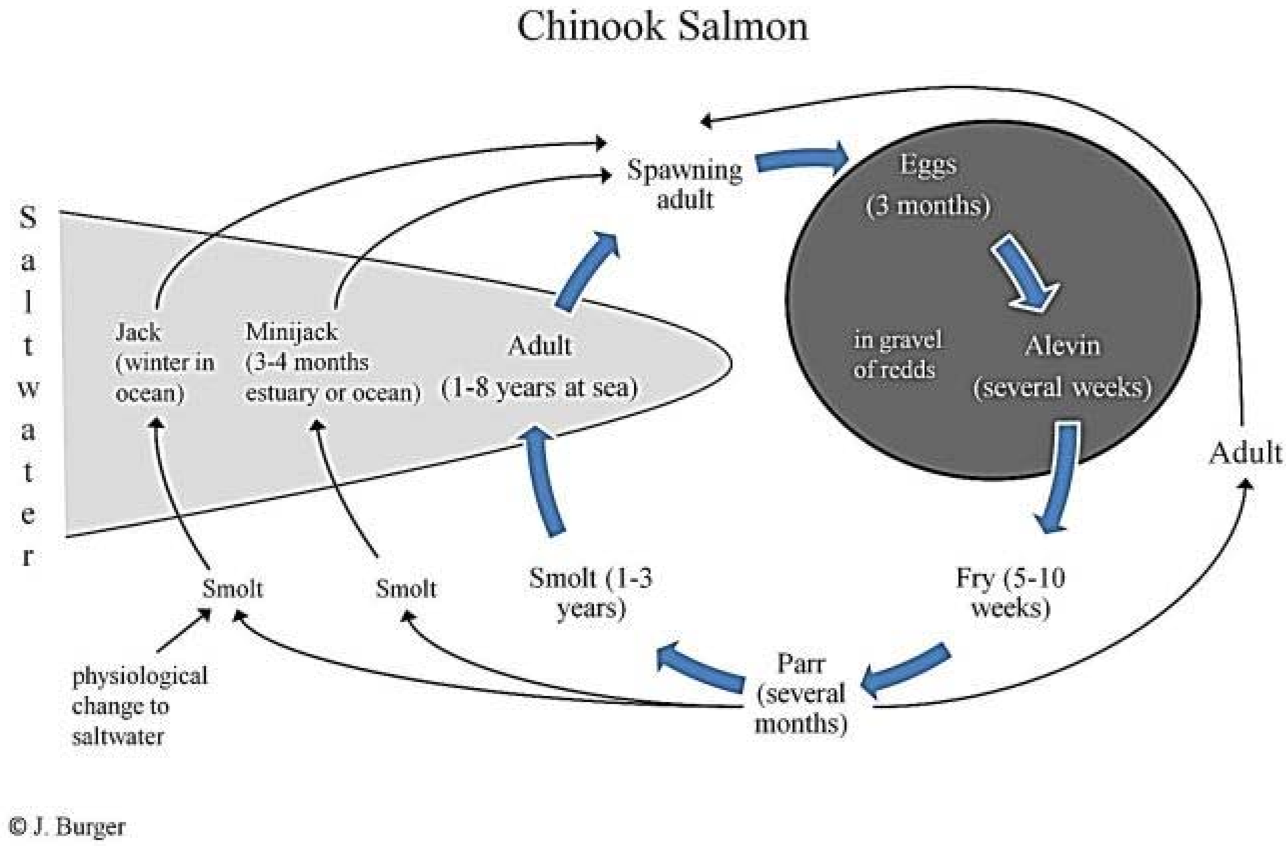

Fig. 2. Life History of the Chinook Salmon in the Columbia River and Pacific Northwest (after Connors et al. 2005, Williams 2006, Johnson et al. 2012). Temporal patterns of different life stages are variable.

Salmon require a relatively narrow range of characteristics for spawning (references in Table 1). The spawning areas need downward flow of water through the part of the nest where the eggs are located (eggs are up to about 45 cm below the surface, Geist 2000). River water must enter at least to these depths to provide oxygen. Fall spawning criteria developed by Hanrahan et al. (2004) included water depth (0.30-9.5 m), velocity (0.23-2.25 m/sec), substrate (25-305 mm grain size), and channel bed slope (0-5 % slope). Although these ranges appear broad, they only co-occur in a very few areas reachable by the salmon. The salmon prefer nesting in areas with water velocities greater than 1 m/s, and where streamflow fluctuations are low (Hatten et al. 2009). Excessive fine sediment impairs egg survival (Honea et al. 2009). Geist et al. (2000) estimated that water velocities between 1.4 and 2 m/s, water depth 2-4 m, and lateral slope of the riverbed of less than 4 % were ideal for spawning habitat. Optimum dissolved oxygen is about 9 mg/L (Geist 2000). While most redds occur in main channel areas, some can be constructed in shallow side channels (Battelle 2003). Thus, there are rather specific habitat requirements for spawning Fall Chinook Salmon, and these requirements may be threatened by climate change if it affects stream flow in the Columbia River (Donley et al. 2012).

A full description of the characteristics required for spawning are provided in Appendix A, but a brief listing is provided below in Table 1.

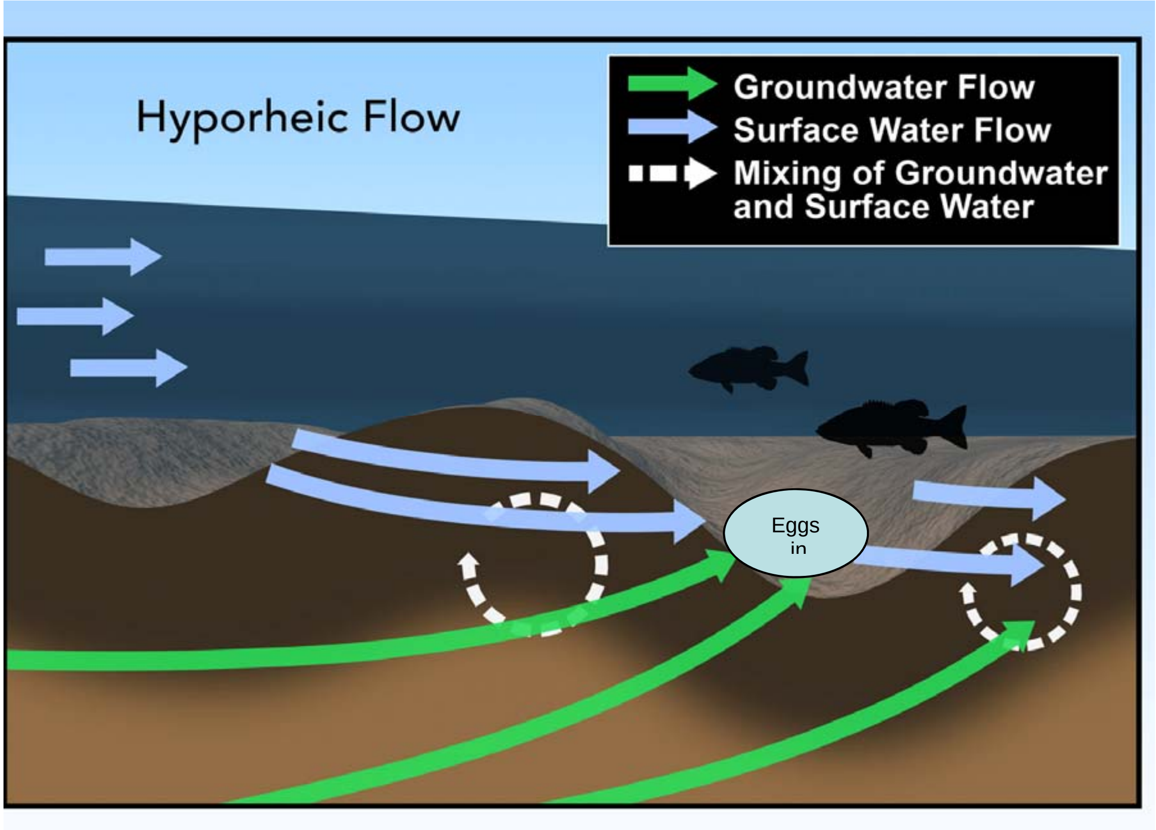

Fig. 3. Schematic of Flow Patterns of pore water upwellings meeting river water in the hyporheic zone where spawning salmon deposit eggs in redds (Courtesy of A. Bunn et al. 2012).

While most attention has been devoted to habitat characteristics within freshwater systems, water quality and landscape scale habitat parameters are important in predicting recruitment of Chinook Salmon (Dauble and Geist 2000, Regetz 2003). Three factors accounted for salmon recruitment: percent of land that was urban, proportion of stream length failing to meet water quality standards, and an index of the ability of streams to recover from sediment flow events. The latter was considered a surrogate for reduced cover and increased siltation (Regetz 2003). Further, conceptual models that are based on the relationship between life history and habitat, in the 19th and 20th centuries, are a useful approach to analyzing management issues with salmon over large areas of the Columbia River Basin (Lichatowich and Mobrand 1995). Runs in this time period can sometimes be estimated from historic commercial catches (Chapman 1986).

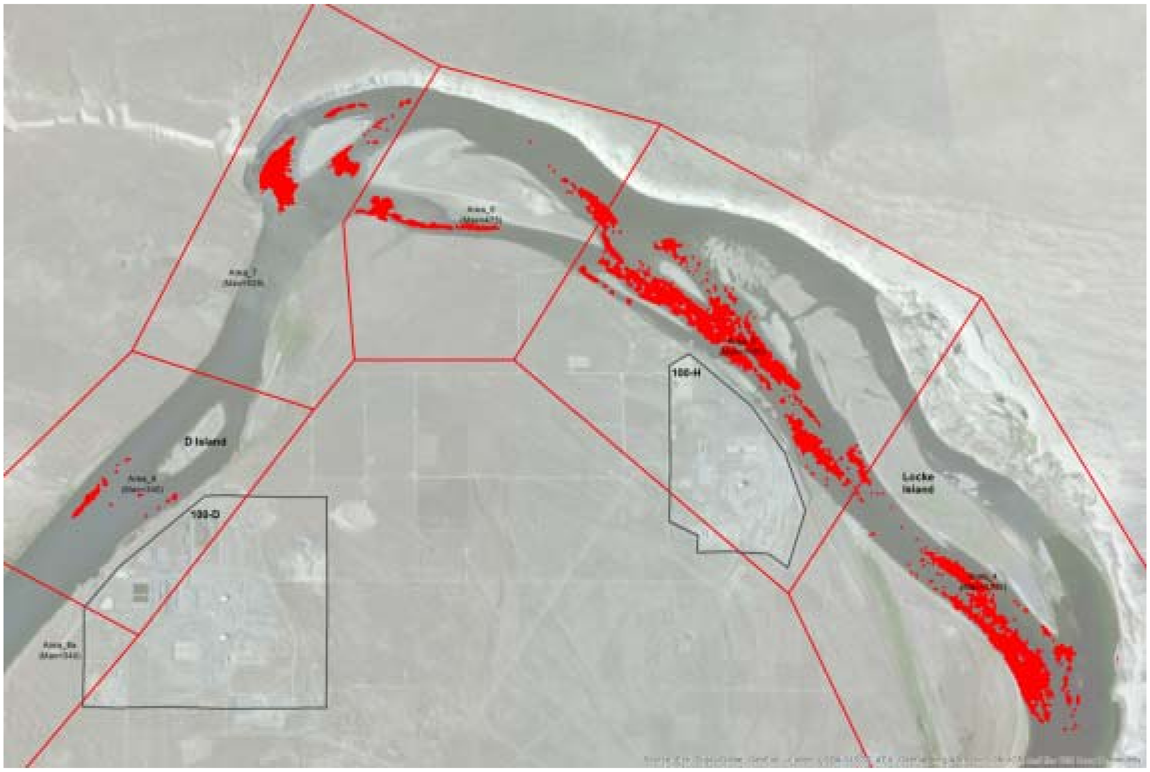

Fig 4. Spawning Locations for Fall Chinook Salmon (indicated in red) in the mid-Columbia River adjacent to the Hanford Reach (after Dauble et al. 2003; GIS prepared by K. Brown, pers. comm.). There are other key areas, including Venita Bar, as well as in the Snake River (Mueller and Ward 2010).

While not usually considered in most discussions of salmon reproduction and population dynamics, the comments by Dauble and Geist (2000) and Regetz (2000) concerning potential landscape scale effects on salmon lead us to consider the broader factors impacting salmon. Much of the research dealing with habitat requirements for salmon deal with physical features of the spawning and rearing rivers and streams, such as water velocity, amount and depth of water, oxygen levels, and particle size (Table 1 and Appendix A). These are a function of water flow, which in turn is a function of environmental factors (e.g. extent and pattern of snowfall and rainfall. The average precipitation of 7.1 inches/year, is highest in December and January. (http://wrcc.dri.edu/cgi-bin/cliRECtM.pl?warich), management (i.e. dam management, adjacent land management), and river physiognomy.

Factors affecting water flow and river physiognomy have been examined by Roseberry and Furbish (2013) for Locke Island, one of the key spawning areas for salmon in the Hanford Reach (Wagner et al. 2013). Although Locke Island is a relatively small area, it is a critical part of the Hanford Reach for salmon because the river areas around it provide some of the most suitable spawning areas in the Hanford Reach (see Fig. 4 above). Roseberry and Furbish found, using high-quality channel bathymetry, that the river in the vicinity of Locke Island has experienced changes in flow due to channel constriction on the east side of the island. Decreases in channel width as a result of landslides divert flow to the unobstructed west side of the island.

These changes in flow may have important consequences for salmon spawning, because of decreased quality or quantity of habitat suitable for redds.

Table 1: Key Characteristics for Redds and Spawning of Chinook Salmon in the Columbia River and tributaries. This refers to Chinook Salmon in general, and not just to studies conducted along the Hanford Reach.

Characteristic	Optimal values	References
General	Gravel beds, with less than 10 m of water, with low water velocity fluctuations.	Papers in Table 1.
Grain size	No fine material, but rather gravel 2.5 to 15.0 cm. Less than 5 % fine grain	Groves and Chandler 1999
Water depth	0.3 – 9.5 m	Hanrahan et al. 2004 2005 (check date); Hatten et al. 2009
Water velocity	Values range from 0.23 to 2.25 m/sec, some authors report greater than 1m/sec	Geist et al. 2000; Hanrahan et al. 2004 2005 (check date); Hatten et al. 2009
Stream flow fluctuations	Reduced, will not spawn with great fluctuations	Beckman and Larsen 2005; Hatten et al. 2009
Dissolved Oxygen	9mg/L	Geist et al. 2000
Channel bed slope	0 to 5 %	Geist et al. 2000; Hanrahan et al. 2004, 2005
Hydraulic conductivity	0.009 to 0.21 cm/sec	Arntzen et al. 2001

Other factors affect salmon spawning habitat, either directly or indirectly (through water flow), up-river from the Hanford Site, as well as along it. The effects of snowfall and rainfall on river flow and depth (and thus on salmon spawning habitat) are well-established, as are the effects of management of water flow by hydroelectric power facilities. Perhaps less obvious, at least initially, is the effect of land management adjacent to the Columbia River on salmon spawning habitat. These include bulk-heading, mining operations, agricultural run-off, and erosion and siltation caused by development adjacent to the river. The latter currently includes DOE remediation practices, such as deep excavation in the 100 Area to remove soil contaminated with chromium that represents a future source to groundwater (DOE 2012, French 2012). De-watering associated with agricultural irrigation is a primary cause of reduced riparian habitats along many stretches of the Columbia River (although not adjacent to the Hanford Site), as well as increasing erosion and sedimentation processes (NRC 1996, Stanford et al. 2006). Logging can affect both erosion (a negative impact) and the amount of wood entering streams and rivers (positive because wood debris is integral to the development of habitat and to deflect heavy water flow, Stanford et al. 2006). Some of these factors are illustrated schematically in Figure 5.

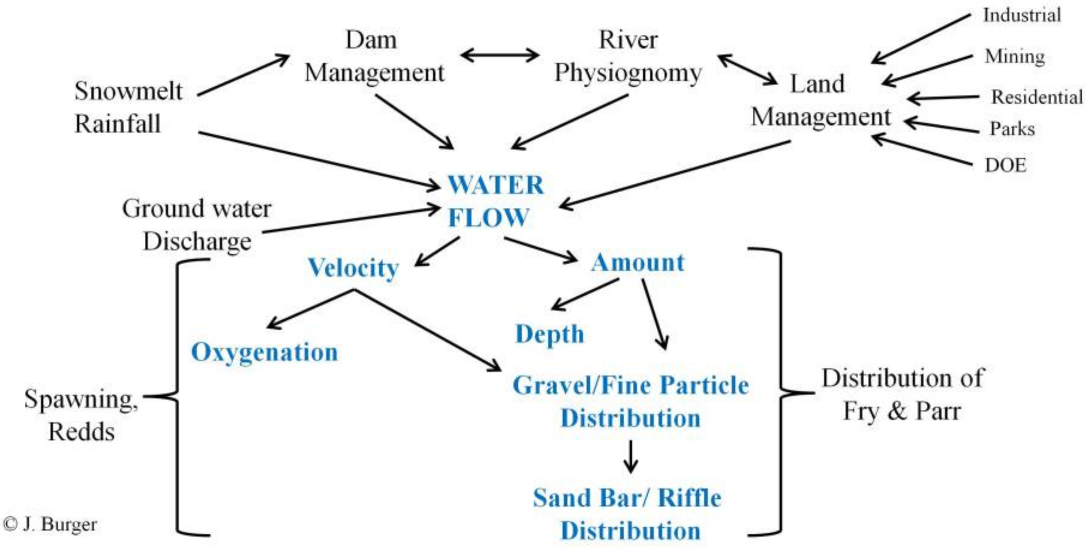

Fig. 5. Schematic of interactions of Some of the Factors Affecting Water Flow in the Columbia River, which in turn Affect the Physical Characteristics that are Important for Spawning and Other Life Stages of Salmon. Developed from several sources in Appendix A.

Upstream urban, mining and industrial effluent, and agricultural runoff and erosion also must be considered because of the potential of contamination of the Columbia by a variety of agricultural and other chemicals and silt. Tern and cormorant predation at the mouth of the Columbia River can be severe (up to 17 % of smolt) because of the presence of dense nesting colonies of these fish-eating birds (Collis et al. 2001, Schreck et al. 2006, Good et al. 2007), Extensive control measures to destroy or relocate the bird colonies have been implemented with only partial success (USFWS 2005,??)

Additionally, there is concern about the potential impacts of hexavalent chromium on salmon eggs and young (OHWB 2002, Farag et al. 2000, 2006a), although one study found no negative effect on fertilization (Farag et al. 2006b, see below). Climate may affect different Chinook populations differently (Levin 2003). Tribal fisherman, for example, report changes in the timing of salmon spawning, and in the length of spawning, and some attribute these changes to climate change (L. Greene, pers. comm.).

The primary habitat requirements for maintaining viable populations relate to the time young salmon spend in estuarine and freshwater habitats because these habitats are manageable (i.e. it is more difficult to manage marine environments for the adult salmon). Adults return to their natal streams to lay eggs, the eggs hatch and fish remain in streams and rivers until they migrate to the sea. Assessment endpoints thus primarily relate to freshwater characteristics of salmon. These include water flow, water depth, pebble size, bank slope, and dissolved oxygen (physical monitoring), conspecific nesting density, food availability and reproductive measures (ecological monitoring), landscape effects on nesting habitat (such as sediment runoff from terrestrial construction or remediation), contaminants and abnormalities in different stages (ecotoxicological monitoring), salmon landings, size and health of the salmon, contaminant levels toxic for consumption (human health monitoring), and monies derived from salmon fishing licenses, fish hatcheries, and other businesses associated with salmon fishing, as well as the cultural and nutritional benefits for Native American Tribes (cultural/economic, Landeen and

Pinkham 1999, Lambert 2008, Burger et al. 2010). The Nez Perce's seasonal calendar lists salmon in 4 of their 17 resource gathering phases (Bohnee et al. 2011). The Tribes affected by the Hanford Site are co-managers of Columbia River fisheries with state agencies (Bohnee et al. 2011). Trends in salmon numbers, and spawning activity (sustainability), are of concern to the Tribes. When the different phases of monitoring are considered together, managers, public-policy makers, and the public should be able to evaluate appropriate management and conservation actions to improve habitat.

Much of the attention in this document is devoted to spawning and habitat selection in redds because they are place-based, but it is equally important to consider the habitat requirements of other life stages. Upon emergence from gravel, fry are mobile, but mobility is limited and fry can easily be forced to change habitats by dry downs or be washed downstream by heavy water flow. Further, the swift-moving water above where redds are typically placed, results in the fry being swept away from the nests (R. Jim, pers. comm.). Thus, regulated water flows that fluctuate rapidly can seriously impact young fry (Stanford et al. 2006). Young fry feed on invertebrates and small vertebrates, usually in riparian habitats (papers in Williams 2006), and suspended sediments can reduce the ability of fry to see and capture prey. Juveniles seek low velocity habitats that afford cover, steady supply of food, and a refuge from large predatory fish (Stanford et al. 2006). Dauble et al. (1989) found that zero-aged Fall Chinook salmon occurred primarily in shoreline areas of reduced current velocity. Salmon migrants in the Hanford Reach exhibited patterns of distribution in the water column that were mainly related to size. The smaller, zero-age Fall Chinook preferred the shallower shoreline areas. Thus, juveniles could be close to the river bottom in shallow water, and potentially exposed to groundwater through seeps and upwellings (e.g., contaminants from DOE sites), as well as to contaminants from surface water runoff (e.g., agricultural or mining runoff). Fry can also be swept by currents to still-water (backwater) at the shallow edges of the river, where they may remain for weeks, and thus could be exposed to upwellings there (G. Bohnee, C. Buck, pers. comm.). The degree of movement of fry and parr (older juveniles) will greatly influence their vulnerability to such contaminants. The factors controlling the movement of fry from spawning beds are not well known or studied (Healy 1991), although downstream movement of fry occur mainly at night (Reimers 1971), which is usually considered an anti-predator strategy.

Another way to examine salmon life history and habitat cycles is to look at the potential overlap in when different stages occur, and to examine variability in life history phases by month (Fig. 6). Figure 6 shows the variability in individual Fall Chinook Salmon spawning in the Columbia River results in relatively long periods when different stages of salmon can be vulnerable. Fall Chinook Salmon begin arriving in spawning areas in late summer (Wagner et al. 2013).

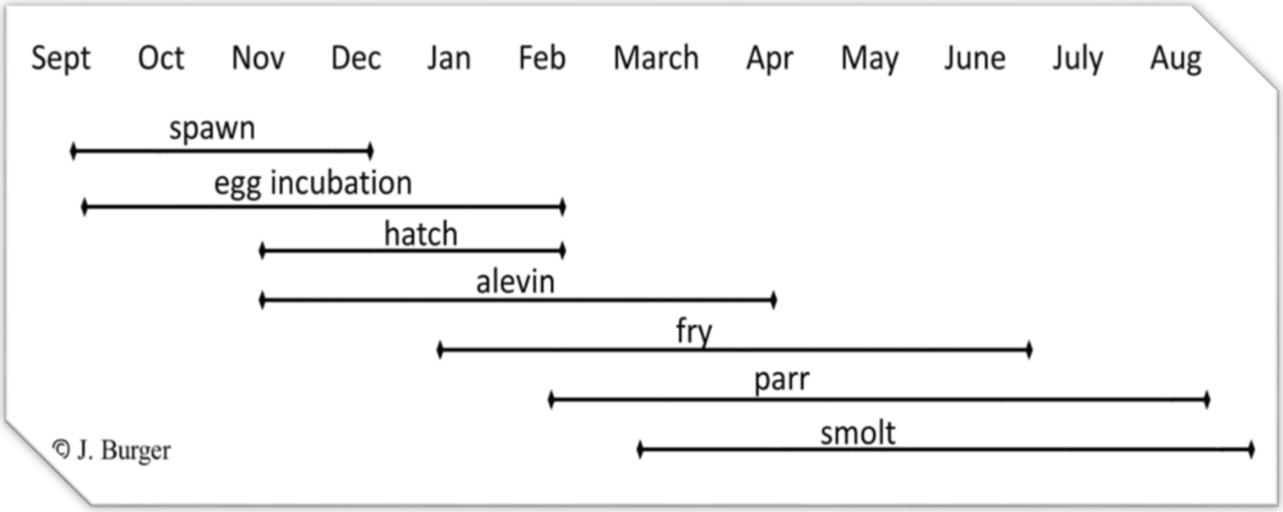

Fig. 6. Generalized diagram of temporal Overlap in Life Cycle Stages of Fall Chinook Salmon in the Columbia River, derived from several sources. Life cycle stages of Fall Chinook adjacent to the Hanford Site will be more restricted temporally.

Populations Spawning in the Columbia River

Much has been written about population levels of salmon in the Columbia River, and populations have been monitored primarily at the dams where fish are counted as they swim-up fish ladders to reach spawning beds. These counts provide a rich source of data for several species that are beyond the scope of this report. There are a number of issues that must be considered when considering data from counts at dams:

1) The presence of dams themselves changes the "traditional" migration patterns because some fish are blocked completely, and some are not strong enough to swim-up the structures at dam (fish ladders),
2) Salmon that do not successfully move up a given dam may not spawn, or they may choose to spawn in the section of the river where they are, and
3) Counts are indices, and not complete population censuses. Adult salmon are counted going upriver to spawn (and not downriver), and not during other life stages.

Even with limitations, these counts are the best available data on salmon populations. Salmon that pass the McNary Dam can go up the Snake River (where they may be counted at Ice Harbor Dam) or continue up the Columbia River (Fig. 7). Those following the Columbia River can either spawn along the Hanford Reach or below the Priest Rapids Dam, or continue upriver to be counted at the Priest Rapids Dam. Examining differences in Chinook Salmon counts at these locations provides some indication of population levels in the Hanford Reach.. Subtracting the Priest Rapids and Ice Harbor counts from the McNary count provides an estimate of the salmon remaining in the Columbia River and the Hanford Reach.

Subtracting salmon counts and Priest Rapids and Ice Harbor, from the McNary Dam counts, gives an estimate of the population that might spawn in the Hanford Reach (Fig. 8). It is essential to remember, however, that these numbers represent Chinook Salmon that spawn all year, which includes the spring, summer and fall runs of Chinook Salmon. Some salmon go up the Snake River to spawn, and there is some movement between segments of each river (Columbia, Yakima, Snake, Liss et al. 2006). Figure 9 shows the number of fish that are presumed to have remained in the Hanford Reach to spawn, but some of the others may well have gone through the Priest Rapids Dam, or the Ice Harbor Dam, and then returned to the Hanford Reach to spawn. Liss et al. (2006) reported that individually marked salmon did just that.

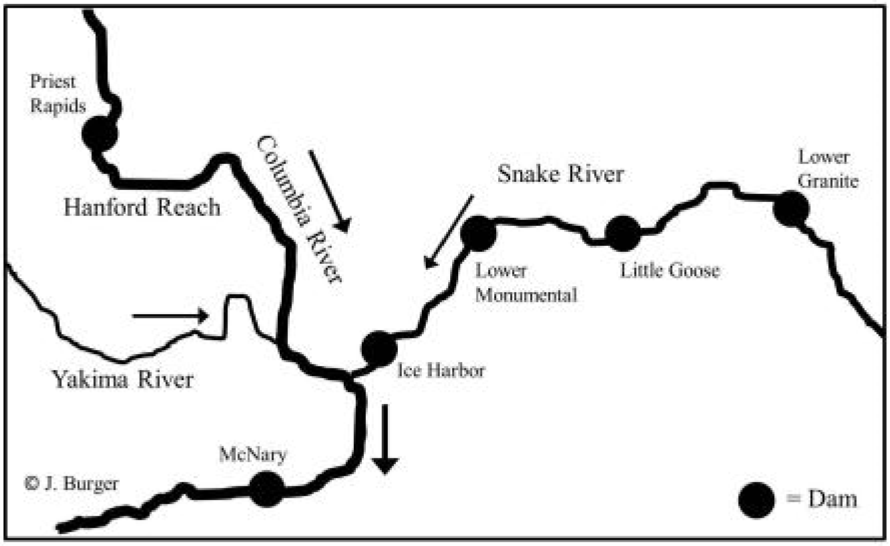

Fig. 7. Schematic of Possible Migration Routes of Salmon after Passing through the McNary Dam on the Columbia River. Direction of river flow indicated by arrows.

The number of Chinook Salmon counted at McNary Dam below Hanford, and at Priest Rapids Dam and Ice Harbor Dam are shown in Figure 8, including adult Chinook (those that migrated to the sea) and jack Chinook (those that remained in freshwater and reached adulthood in about a year (Columbia Basin Fisheries, Agencies, and Tribes (CBFAT, 2013). Note that similar data for other salmon species at these two dams are provided in Appendix B. The data indicate relatively constant populations during the 1960s and 1970s, with increases in the 1980s and thereafter.

In Figure 9, the lowest line represents the number of Chinook Salmon counted at Priest Rapids Dam. The middle line indicates salmon counted at Ice Harbor Dam. The top line indicates the McNary Dam counts. The blue area indicates the salmon that stayed in the Hanford Reach and presumably spawned there.. This includes all Chinook Salmon runs, not just the Fall Chinook. Most of the spring run Chinook Salmon go up the Snake River, accounting for the large number shown in red.

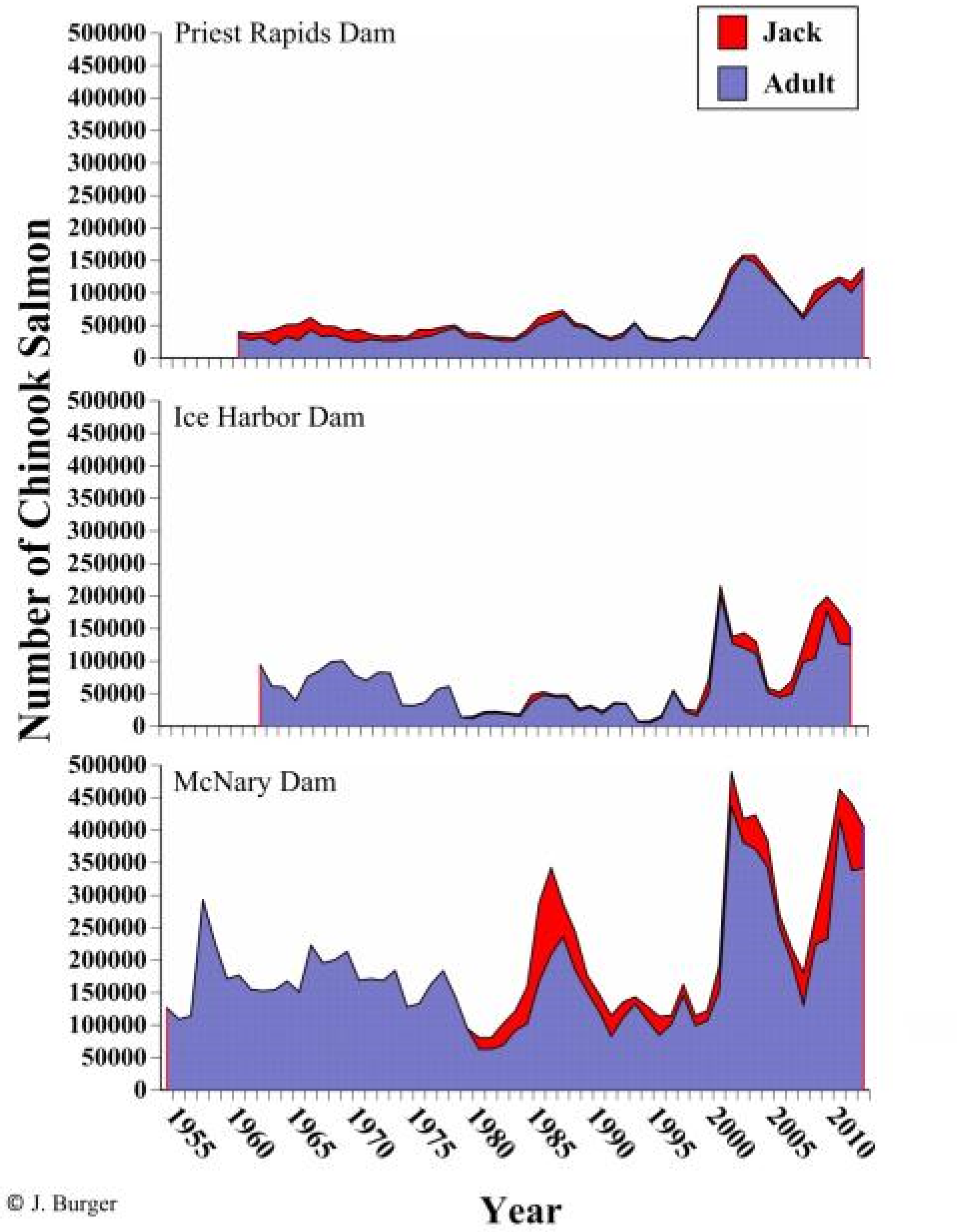

Fig. 8. Numbers of Chinook Salmon Counted at McNary and Priest Rapids Dams on the Columbia River and Ice Harbor Dam on the Snake River (CBFAT, 2013). These numbers reflect all Chinook Salmon, not just Fall Chinook Salmon.

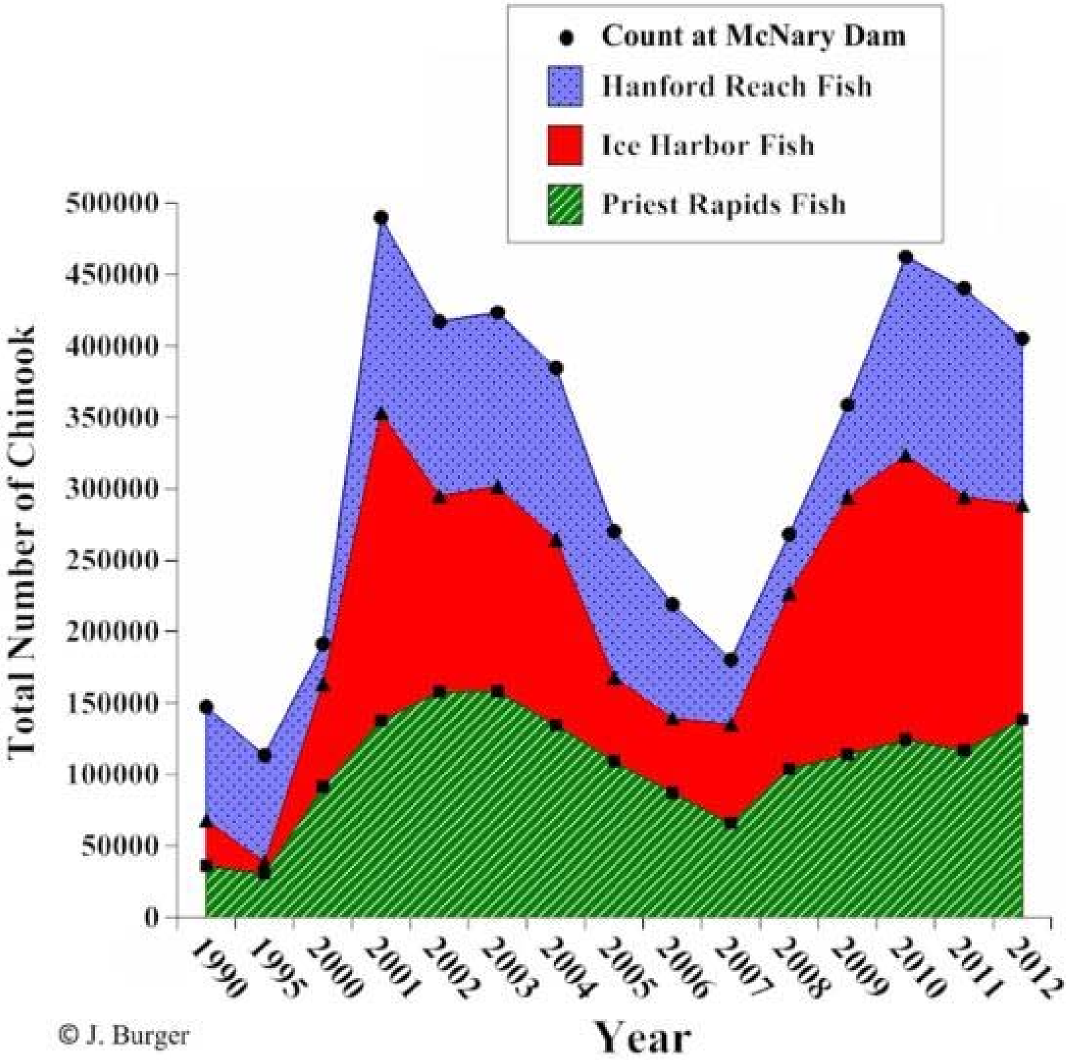

Fig. 9 Number of Chinook Salmon counted at the McNary Dam below the Hanford Reach (top line on the graph), and at the Priest Rapids Dam above the Hanford Reach (lower line). The total fish passing Priest Rapids Dam are shown in green. The fish passing the Ice Harbor dam on the Snake River are shown in red. Thus the fish shown in blue are those that remained in the Hanford reach (data from CBFAT, 2013).

Figure 10 summarizes the Hanford Reach population which varies greatly from year to year. This variation is likely due to natural population cycles, differences in harvesting (and in harvest regulations), and to sampling periods. That is, in some years counting started in March, and in other years it started in April; in some years counting ended at the end of October and in others it ended December 31. Wagner et al. (2013) noted that for Fall Chinook, the main spawning is in November, so counts that ended in October may have missed some spawners.

Even given the variability in sampling salmon at dams, and the natural population cycles of salmon, the number of Chinook Salmon likely spawning in the Hanford Reach has ranged from 25,000 to about 130,000.

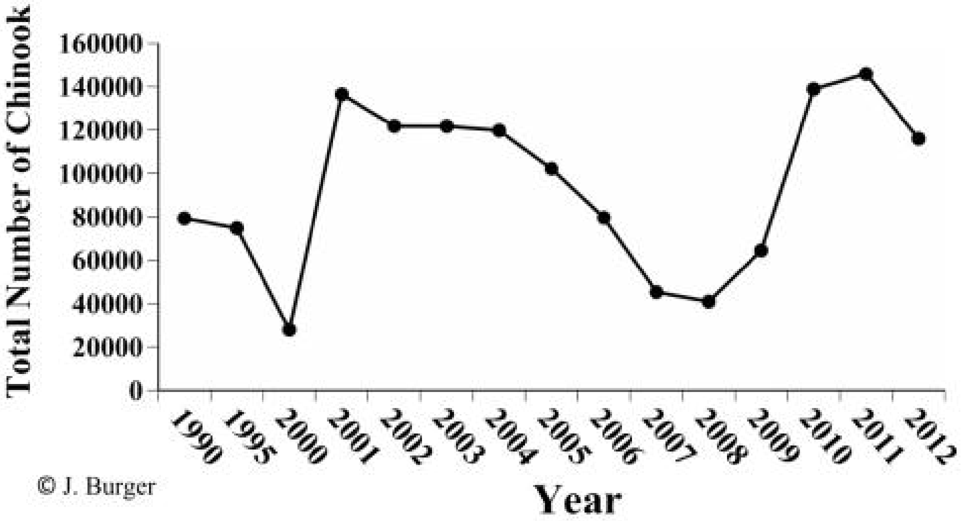

Fig. 10. Salmon that likely remained in the Hanford Reach because they passed by McNary Dam below the Hanford Reach, and did not leave the Hanford Reach via either Priest Rapids Dam (upriver from Hanford) or Ice Harbor Dam on the Snake River.

Other agencies, such as the Washington Department of Fish and Wildlife and Grant County, also compute Chinook Salmon, especially Fall Chinook Salmon. Even so, there are considerable difficulties in estimating numbers and survival of adult Chinook salmon in the Columbia and Snake Rivers (Dauble and Mueller 2000).

Another indication of populations is the number of redds in the Hanford Reach. Redd counts are highly correlated with counts from dams (Wagner et al. 2013). Figure 11 shows the number of Fall Chinook Salmon redds in the Hanford Reach (the data were derived from Dauble and Watson 1997, Liss et al. 2006, and Wagner et al. 2013). These data are an index, rather than direct counts. That is, counts were made of a section of redds during the entire period, but no attempt was made to count all redds. Thus the counts serve as a bioindicator of population trends in spawning activity. These data from 1948 to 2012 for the Hanford Reach clearly indicate population increases, although populations varied from year to year.

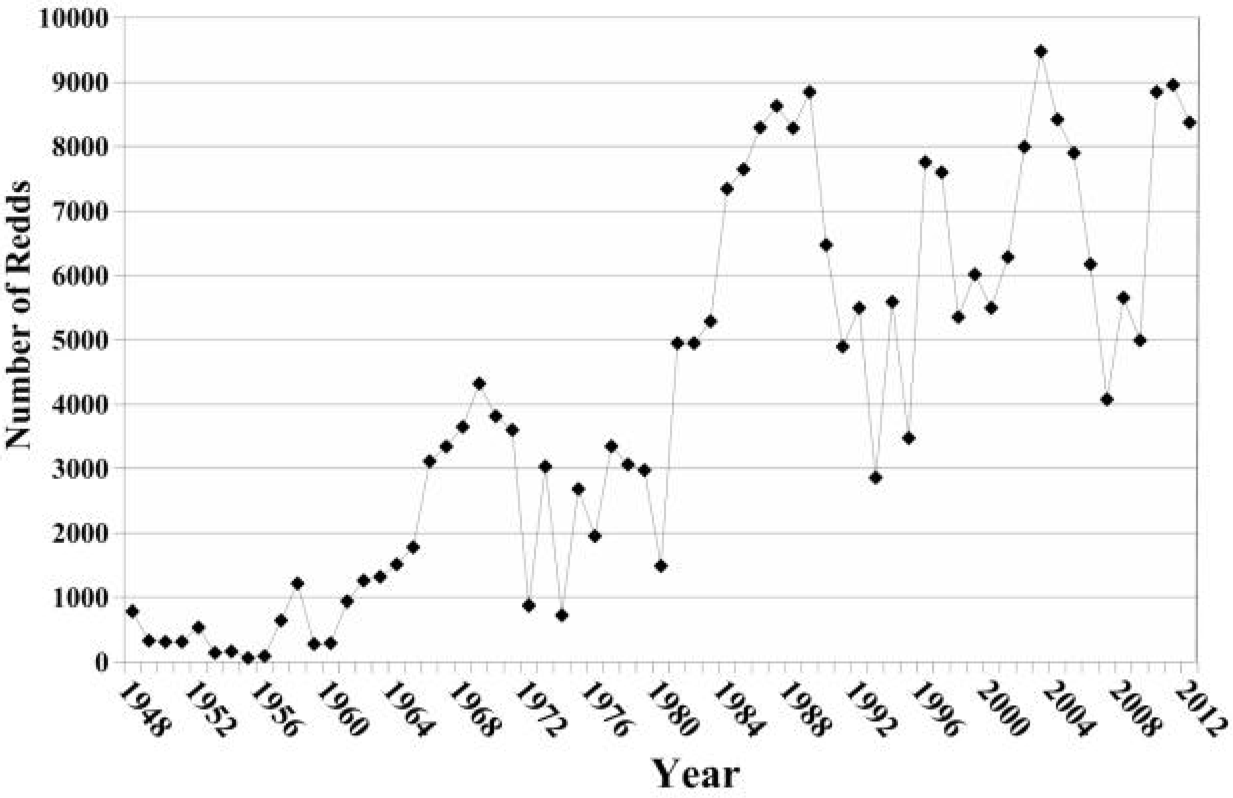

Fig. 11. Number of Redds in the Hanford Reach. Data are from Dauble et al. 2003a, Liss et al. 2006, and Wagner et al. 2013.

While the increase in spawning in the Hanford Reach may be due to reduced harvesting, supplementation from hatcheries, and better hydropower management, it is also possible that the increase in spawning is due to decreases in suitability of spawning elsewhere, dams that block progress farther up the Columbia from Hanford (at Priest Rapids, built in 1959), and dams on the Snake River (Ice Harbor). The Hanford Reach is one of only two free-flowing stretches of the Hanford River without dams and bulkheads. Thus, increases may be largely due to decreased suitability and availability elsewhere than to increased favorable conditions in the Hanford Reach (Liss et al. 2006). This viewpoint is partly supported by the finding that a female fall Chinook Salmon marked above the Ice Harbor Dam on the Snake River moved freely between the Snake River, Yakima River, and Hanford Reach for some 80 days, and finally spawned in the Hanford Reach.

The total Chinook redds counted along the entire Hanford Site in 2012 was 8,368, while only 2,264 were counted along the operational area subsections (e.g. near the reactors), which represents 27% of the total redds counted). The Chinook redd distribution counted along the Hanford Site is shown in Figure 12 and Table 2. Aerial counts and aerial photography have improved the ability to determine the number of visible redds (Visser et al. 2002).

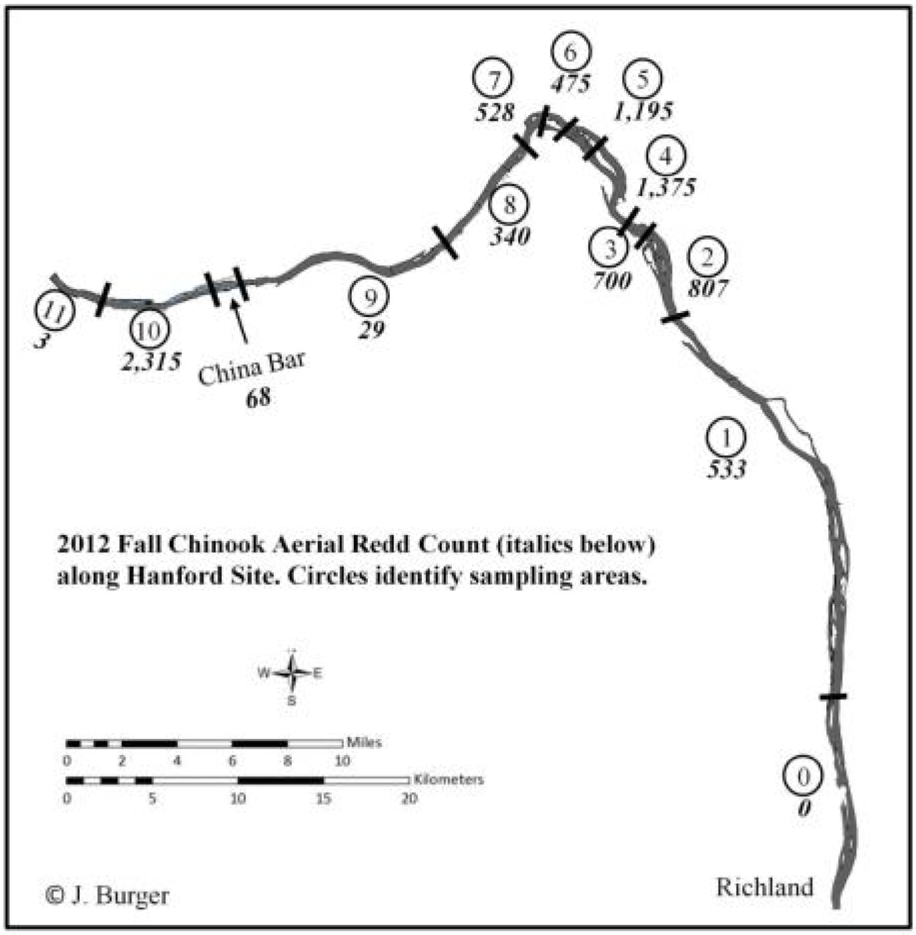

Fig. 12. Distribution of Redds Counted near the Hanford Site in 2012 (data from Wagner et al. 2013). Number in the circles reflects sample area (designated by lines across the Columbia River), and the number in italics is the number of redds counted.

Table 2. Sampled Redd Counts for 2012 along the operational area subsections of the Hanford Site (data from Wagner et al. 2013) aerial survey.

Hanford Site Sub Area	Sample area Number on Map in Fig 12.	Maximum Count
300 Area	0	0
Dunes	1	0
100F	2-3	700
100H	5	1,195
100D	8	340
100N	8	0
100K	9 (nearest 8)	0
100BC	9	29
TOTAL		2,264

Factors Affecting Population Levels

A large percentage of the Fall Chinook Salmon in the Columbia River spawn along the Hanford Reach (OHWB 2002), and there are several factors that affect population levels of salmon. Books have been written about Pacific salmon (NRC 1996, Groot and Marcollis 2003, Williams 2006), and the main issues discussed extensively in these books and in the refereed literature include species and genetics, life histories, population structure and dynamics, habitats, human history and influences, hydroelectrical systems and mitigation, artificial production (hatcheries), harvest management, estuarine and marine environments, conservation, and recovery and restoration plans, as well as values and ethics There are literally hundreds of papers on these topics for various salmon and related species.

Another way to evaluate the factors affecting salmon populations is to examine the restoration measures proposed to enhance salmon populations in the Columbia River. A full description of the measures can be found in Appendix C. It is clear that many fisheries biologists concerned about salmon consider that recovery depends upon management of hatcheries, hydrodams (water flow, fish ladders), and harvesting. Restoring normative water flow is a primary factor. A summary table is given below (Table 3).

We used these sources on the factors affecting populations (Table 1, Appendix A), and possible recovery measures (Table 3), to develop a conceptual model of the factors that affect salmon populations (Fig. 13). Many of the factors in Figure 13 are discussed above in the life history and habitat section (harvest, Native American use, dams, hatcheries). Similarly, the types of factors affecting salmon were discussed. Although beyond the scope of this report, natural resource trustees have figured prominently in affecting the regulation, management, and protection of salmon. Figure 13 illustrates the factors affecting salmon directly, but other external factors affect water flow and the river physiognomy on a landscape scale (refer back to Fig. 5), which affect riverine habitat suitability. While contaminants do not figure prominently in any discussions of these factors, we nonetheless include them in the model.

Table 3: Summary of Measures to Increase Salmon Populations (particularly Chinook in the Columbia River). Basic to restoration is an information base sufficient to design restoration and management practices. The complete data can be found in Appendix C at the end of the document.

Species (stage)	Method	Reference
Chinook-smolt	Increase smolt hatchery releases Provide bypass at dams or transportation around dams Change river flow to decrease smolt delays	Raymond 1988
Chinook (fall)	Establish normative flow regimes	Dauble et al. 2003a
Salmon	Maintain correct thermal characteristics	Goniea et al. 2006
Salmon	Restoration of habitat for all life stages Reduce mortality, including harvest Plan hydropower mitigation	Williams et al. 1999

Species (stage)	**Method**	**Reference**
Salmon in estuaries	Restore estuarine habitat Plan hydropower mitigation Restore normal river flow Time hatchery releases to reduce bird predation	Bottom et al. 2004;Collis et al. 2001
Salmonids	Conduct necessary life–cycle studies, particularly on survival, using tagging studies	Skalski 2003
Mainstream Chinook Salmon	Dam breaching and flow management (breach 4 lower Snake river dams Reservoir drawdown (phased drawdown of McNary Reservoir) Engineering fixes	DOE/BP 2008
Chinook in Hanford Reach	Hold stream flows steady during peak spawning Recovery actions aimed at harvest, hatchery, hydro and habitat Restore connectivity Address entire network, interconnections Address cultural aspects	Hatten et al. 2009;UCSRB 2007;Liss et al. 2006
Salmon Hanford Reach	Conduct effects studies with chromium and other contaminants o determine if they are a factor impeding recovery (DOE, EPA, others)	OHWB 2002 Bisson et al 2006

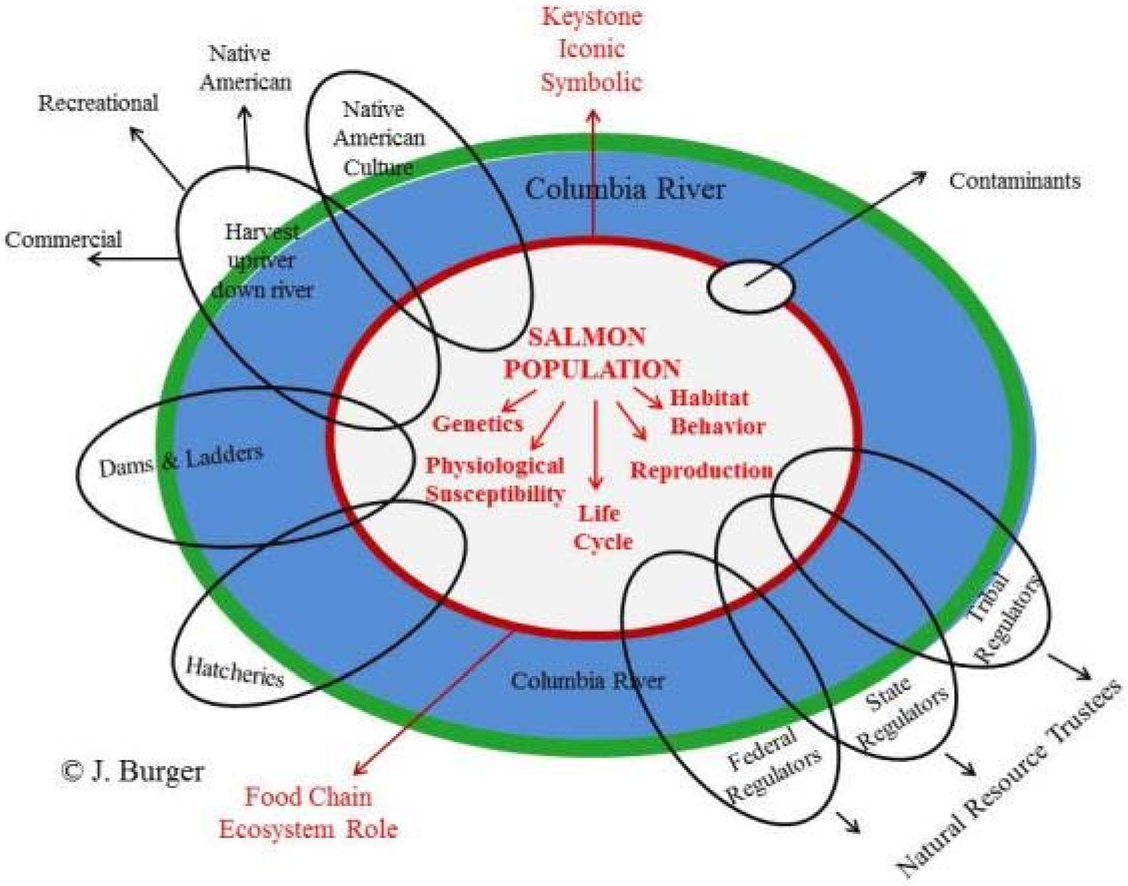

Figure 13. Schematic of Factors affecting Chinook Salmon populations in the Columbia River. Salmon are affected by internal (shown in red) and external factors (egg-shaped factors operating terrestrially and in the Columbia River). Information developed by J. Burger from many of the sources listed in the references.

In some books about Pacific Salmon, toxics, chemicals, and chromium are not even mentioned in the index (e.g., Groot and Marcollis 2003), nor is Hanford mentioned except to note that the strongest populations of fall Chinook occur along the Hanford Reach (NRC 1996). *Return to the River: Restoring Salmon to the Columbia River* (Williams 2006) also does not mention chromium, although it does mention aluminum, sewage, pulp mills, and metals from mining. Williams notes that “water pollutants, other than fine sediments, increased temperature, and metals from mining districts, generally are not considered a major factor in salmonid declines nor particularly problematic for recovery,” then adds “we are not sure that the available data have been examined well enough to agree with this consensus,” and “interactions between maintenance of salmonid critical habitats for all life stages has not been examined extensively in the Columbia River system” (Williams 2006, page 211). These comments form a background for our examination of laboratory experiments on the effects of chromium on salmon.

It is, however, important to put the analysis that follows in perspective. In Figure 14 we expand the contaminants section of Figure 13 to reflect the factors that influence toxicity, as well as sources. Factors are both physical (source) and biochemical. It is important to consider all sources of contamination to the Columbia River including upstream mining, agriculture, industries, and urban areas, not just Hanford. Contaminants (including chromium) can enter the river through seeps and upwellings directly from the Hanford Site (DOE 2011). There is also a direct pathway from the sources to the river through run-off and deliberate releases – and some tribal observers note that run-off could be increased by DOE's environmental remediation activities (such as massive digging to remove contaminated soil, R. Jim, pers. comm.). We should also note that we do not address the possible effects of past chromium releases into the Columbia River, which could have had effects on fish, with cascading effects to the food chain.

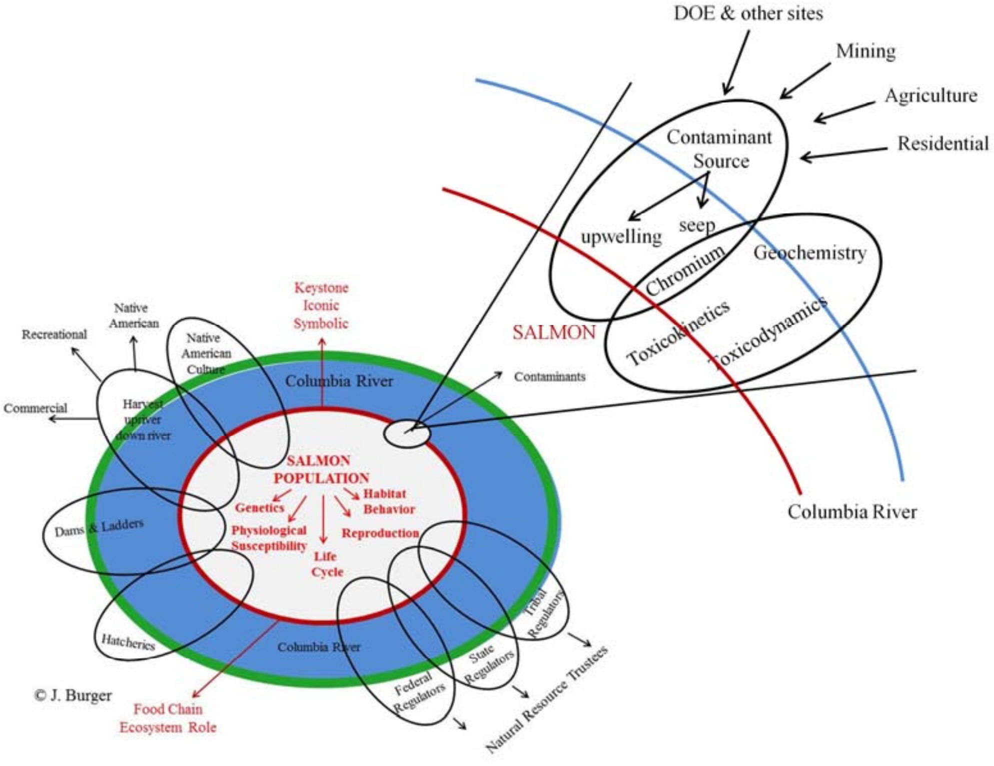

Fig. 14 Schematic of Factors Affecting Toxicity of Chromium in Salmon in the Columbia River. Salmon are at the center, surrounded by the Columbia River (in blue).

Potential effects of chromium on salmon are a function of environmental fate and transport (is there a completed pathway from chromium sources to any life stage of salmon?), and toxicokinetics (uptake, distribution, and elimination) within salmon. The former is a function of chromium from upwellings and seeps that result in chromium in the pore water (that bathes the incubating salmon eggs in redds), while the latter is a function of contact, absorption, distribution within the body (toxicokinetics) and the toxicodynamic aspects of cellular, biochemical and physiologic responses of salmon tissues and organs. These same processes would function for any contaminant that is carried via groundwater to pore water, to eco-receptors.

Role of Toxic Chemicals and Chromium

The role of toxic effects of chemical and radiologic contamination can be considered from several viewpoints: 1) thresholds for toxic effects (from laboratory and field experiments and bioassays), 2) effects on individuals and populations, 3) relative adverse effects of toxic chemicals compared to other factors (e.g. fisheries, hatcheries, habitat loss, see above), and 4) potential for influencing population levels by reducing chemical exposure (source reduction). In this context, the role of one chemical compared to another is also important. Further, the relationship of toxic effects levels and regulatory standards or criteria are important for understanding potential effects, in addition to meeting regulatory requirements. These are defined in the box below.

EFFECT LEVELS USED IN RISK ASSESSMENTS

There are several terms to bear in mind when considering toxic effects and dose-response curves. Each of the following is experiment-specific and end-point specific. A single study would have separate values for each endpoint listed. The NOAEL and LOAEL are widely used in risk assessment. The NOEC and LOEC are widely used in aquatic toxicology

NOEC: No observed Effect concentration is the highest concentration at which no effect is observed.

NOEL: No observed effect level. The highest dose at which the endpoint is not detectable. Endpoint can be anything measurable and biologically trivial. They are not usually used in standard-setting.

NOAEL: No observed adverse effects level. The highest dose or exposure at which no biologically significant or “adverse”.

LOEC: The lowest non-zero concentration at which some effect or some significant effect is observed.

LOEL: Lowest observed effect level (can include trivial endpoints that are disregarded in risk assessment and management). The effect may be statistically significant but not biologically significant.

LOAEL: The lowest non-zero dose or exposure at which a biologically significant adverse effect occurs. Usually if a NOAEL is identified, then one does not pay attention to the LOAEL; the NOAEL takes precedence in risk assessment.

Maximum Acceptable Toxicant Concentration: This is usually defined as a point between the NOEC and the LOEC, and is the geometric mean of these two values.

Threshold: The point in the dose-response curve where an effect occurs of can be detected This may be equivalent to the LOAEL or may be interpolated between a NOAEL and a LOAEL.

Various agencies, including the U.S. EPA use these values to arrive at criteria, for instance EPA's Reference Dose (RfD) for human health. After reviewing literature, the agency identifies a particular study (sometimes from among thousands) which provides a relevant endpoint, and identifies the NOAEL for that endpoint. The NOAEL is then divided by uncertainty factors (for example interspecies extrapolation) to arrive at the RfD. If, however, effects are detected at the lowest non-zero dose, there is not a NOAEL, and the LOAEL is used instead. In such cases, an uncertainty factor of 10 is included as a rough approximation of the impact of not having a NOAEL (EPA http://www.epa.gov/iris/rfd.htm). Aquatic toxicology studies are usually based on a concentration in water, rather than on a known dose to the organism, hence the NOEC and LOEC are often reported (Holdway 1988). The Maximum Acceptable Toxicant Concentration, is the concentration that is considered "safe", at least for the fish species on which it was derived (Holdway 1988). It is defined as the geometric mean between the NOEC and the LOEC. The Maximum Acceptable Toxicant Concentration for Rainbow Trout eggs and embryos ranged from 50 to 110 µg/L (Sauter et al. 1976) while Brook Trout (*Salveninus fontinalis*) were even more sensitive with MATC ranging from 20 to 350 µg/L. (Holdway 1988 p.386). The lower numbers are equal to the NOEC.

In 2009 EPA wrote a "*State of the River Report for Toxics,*" and at that time the contaminants of concern in the Columbia River they discussed were mercury, DDT and its breakdown products, PCBs, and PBDE flame retardants (EPA 2009). The report summarized "what we currently know about four main contaminants in the Basin and the risks they pose to people, fish, and wildlife" (EPA 2009). The report further mentions that other contaminants are found in the Basin, mentioning "arsenic, dioxins, radionuclides, lead, pesticides, industrial chemicals, and newly emerging contaminants" (e.g. pharmaceuticals), but the report did not mention chromium. The report did note that it was not focusing on effects on the river from the Hanford Site (EPA 2009).

Another approach to understanding toxic chemicals in the Columbia River is to conduct a broad spectrum screen whereby dozens of chemicals are analyzed in water and sediment, and screening risk values are used to evaluate which chemicals are of concern. This approach was followed by the Draft *River Corridor Baseline Risk Assessment* (RCBRA; DOE 2011, see below) (still officially a draft), which used Washington State's Ambient Surface Water Criteria of 10 µg/L for chromium to examine exceedances. At present, Washington Department of Ecology's (WDE) position is that "research to date shows no negative impact to salmon from chromium concentrations in the river gravels, and that juvenile salmon move away from areas where there is chromium in the water." (http:/www.ecy.wa.gov/programs/nwp/salmon.html). Since this Department is one of Hanford's regulators, this is a strong statement.

Understanding whether salmon can avoid chromium is a critical point. Svecevicius (2009) reported that adult Rainbow Trout show an avoidance reaction to Cr(VI) at 2 µg/L, and have other behavioral effects at 59 µg/L. DeLonay et al. (2001) reported that juvenile (parr) salmon can avoid 54 µg/L but not 27 µg/L, but only at low hardness). This avoidance does not occur at high water hardness.

The hardness of Columbia River water is about 80 µg/L of $CaCO_3$. Groundwater has a hardness of about 200 µg/L of $CaCO_3$ (e.g. at base of gravel). The hardness of the pore water is on a gradient between the hardness of groundwater and river water. The experiments of DeLonay et al. (2001) were conducted at hardnesses of 80 µg/L of $CaCO_3$ and 200 µg/L of $CaCO_3$, and with chromium exposures up to 266 µg/L. The lack of avoidance at hardnesses of 200 µg/L of $CaCO_3$, and chromium levels of 266 µg/L may be a result of salmon showing a preference for hard water that exceeds their possible aversion to chromium. The question of salmon avoidance of chromium requires further study. In cold seasons, pore water may be slightly warmer than river water and could attract salmon (R. Jim, pers. comm). It is particularly important to determine whether fry that have just gone through swim-up (moving out of the gravel and entering a phase where they now eat) remain adjacent to the gravel-river interface and are close enough to have higher chromium levels than if they immediately entered the river flow where chromium levels are mainly below the practical quantification limit (3.7 µg/L)

Understanding the role of toxics requires examining the form of the contaminant (speciation in the case of metals such as chromium), levels in media, levels in biota of concern, screening risk levels, and most importantly, effects levels. Each of these will be discussed below. Effects levels can only be determined by controlled laboratory conditions, but field observations of deformities can play a role by identifying possible effects if these effects are correlated with higher levels of a particular contaminant. Although morphological abnormalities in salmon have been reported (Nez Perce, 2000; R. Buck, C. Buck, S. Greene, pers. comm.), the fish with abnormalities (spots, 4 eyes, 2 heads) have not been analyzed statistically (number/fish examined) or chemically.

Chromium Redox Cycling and Implications for Salmon

The major concern about exposure of salmon (and other eco-receptors) to chromium in the Columbia River focuses on hexavalent chromium (Cr-VI). This is the form (mainly as sodium dichromate) that was used for corrosion control in reactor cooling water at Hanford, and great quantities were released in various ways and places. There is abundant literature on the environmental chemistry of chromium and its compounds. Although chromium can occur in valence states that range from -2 to +6, in nature all attention focuses on trivalent chromium (Cr-III) and hexavalent chromium (Cr-VI). In compounds with Cr-VI the chromium moiety is anionic (negatively charged) as in chromates and dichromates or chromic acid. Cr-III is often the cationic component of compounds such as chromium chloride ($CrCl_3$). The interconversion of Cr-VI and Cr-III can be very site dependent, influenced by physical and chemical properties of the soil or pore water, including pH and ion concentrations. Soils rich in manganese (Mn-IV) tend to oxidize Cr-III to Cr-VI, which can have a slower disappearance rate from pore water (Hassan and Garrison 1996).

Hexavalent chromium is of primary concern for six reasons: 1) it is a known human carcinogen, 2) it is highly soluble in aqueous environments including blood, 3) it readily enters cells, 4) it is a strong oxidizing agent, particularly in acid solutions, 5) it is stable in the environment, and 6) in the presence of organic substances in cells, it is readily reduced to Cr-III which binds to macromolecules such as proteins and DNA, disrupting cellular function and predisposing to cancer. Thus the highly soluble Cr-VI is mobile in the environment and the body, where it is readily reduced to Cr-III, which occurs in a variety of complexes with varying solubility and toxicity. Cr-VI is listed as a known human carcinogen, yet it may be the reduced form (Cr-III) or the redox process itself, which actually causes the cancer changes in cells. Cr-III has moderate toxicity, but is not considered carcinogenic, and indeed Cr-III is considered an essential trace element for humans. Cr-III bioavailability and toxicity is influenced by water hardness (more toxic in "soft" water), while hardness has less influence on Cr-VI uptake or toxicity (EPA 1980).

The chromium used at the Hanford reactors and released into the environment was Cr-VI (mainly as dichromate). Most or all of the chromium in groundwater and pore water remains hexavalent chromium (Cr-VI) which is stable under ambient conditions (Figure 15). Hexavalent chromium is soluble and mobile in the groundwater. The interconversion of Cr-VI and Cr-III in the environment depends particularly on pH, on the redox conditions and local chemical/biochemical environment such as the availability of manganese oxide as an oxidizing agent, or organic substances (or microorganisms) that reduce Cr-VI. Under most environmental circumstances, the oxidized Cr-VI is stable, and unless otherwise documented, most measurements of total chromium in environmental media are assumed to represent hexavalent chromium (Cr-VI). The Pourbaix diagram (Fig. 15) is an idealized graphic representation of the stability of different chromium compounds under different environmental conditions.

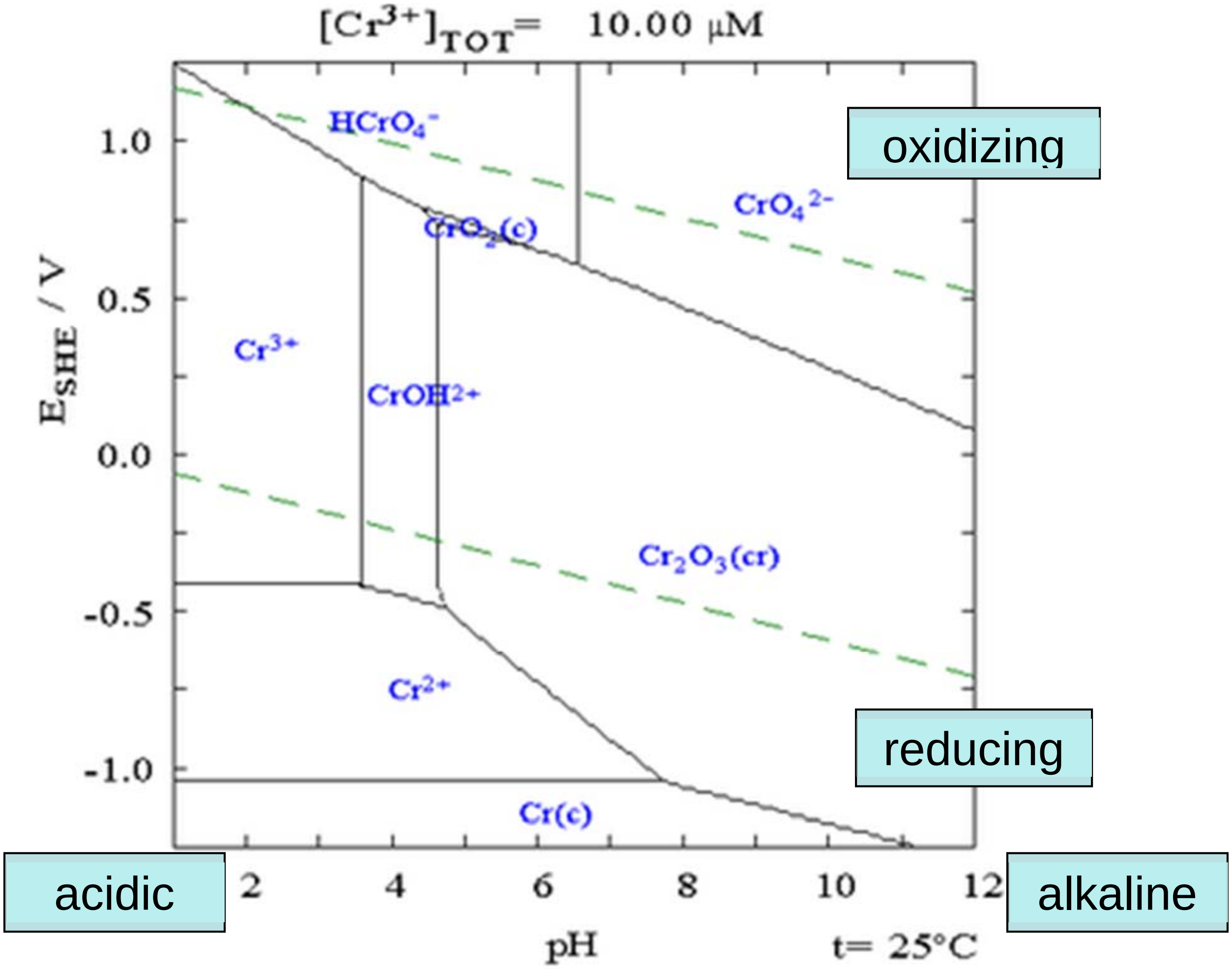

Fig. 15. Pourbaix Diagram for Chromium at 10 μM in Water showing which Forms or Chemical Species are Favored or Stable at Varying Combinations of pH and Oxidizing Conditions. Although pH can be measured directly, the oxidizing conditions are more difficult to quantify (modified from Kotaś and Stasicka 2000). The upper and right side represent hexavalent chromium species. This diagram has not been corrected for water hardness and dissolved organic carbon.

Chromium: Effects and Thresholds

In discussing toxic effects we distinguish susceptibility from vulnerability. Susceptibility refers to intrinsic factors (genetics, heredity, lifestage) which influence response to a toxic, while vulnerability refers to location and behavior that influence access to, contact with, and exposure to the toxic substance. Some fish are intrinsically more susceptible to chromium toxicity than others. Overall, chromium-induced toxicity in fish is influenced by species, age, environmental factors, exposure time, and exposure concentration (Velma et al. 2009). There are both acute and chronic effects on a variety of organs and systems (Velma et al. 2009). In fish, acute effects include cytotoxicity, biochemical toxicity, and hematology and immune system toxicity. Chronic effects include survival differences and growth abnormalities as well as neoplasia, organ damage and functional impairment (Velma et al. 2009).

Chromium toxicity is potentially of concern for salmon because hexavalent chromium is highly mobile in the environment, is present in pore water, and has the potential to cause abnormalities in egg, embryonic, and fry development (Olsen and Foster 1956, Eisler 1986, 2000; Farag et al. 2006b). Chromium effects on salmon need to be considered for different life stages because habitat, mobility, diet and vulnerability differ among life stages. The critical life stages, for the purpose of examining effects and thresholds are: 1) spawning and fertilization, 2) redd stage (eggs and alevins in gravel directly exposed to pore water), 3) fry that may have low mobility, remain in the Hanford Reach, and may spend time close to the gravel surface after swim-up and the initiation of exogenous feeding (Farag et al. 2000), and 4) Parr (older juveniles) that have higher mobility, remain in river water, and may (or may not) migrate downriver, eventually to the estuary.

These life stages as well as smolt and adults, have different susceptibilities and vulnerabilities to chromium derived from the Hanford Site. Juvenile Fall Chinook salmon in the central Columbia River feed primarily on aquatic insects, mainly Chironomidae larvae and pupae (Dauble et al. 1980), so food chain exposures are important. Adult salmon that mature and grow in the ocean, have a different suite of potential exposures, but upon their return to the river are less vulnerable to chromium exposure from the Hanford Site. The migrating and spawning adult salmon are in the river for a relatively short period of time. They do not eat while spawning, and most die shortly thereafter.

Chromium toxicity differs from that of heavy metals such as mercury, lead and cadmium. Fish readily absorb Cr-VI from water through their gills. The chromium accumulates in organs such as the kidney, spleen, brain and bone. Cr-VI is also absorbed through the intestine. At very high concentrations, intestinal and gill damage occur, and respiratory and osmoregulation are impaired (Holdway 1988). However, compared with other metals, chromium toxicity is relatively low. Buhl and Hamilton (1991) tested Coho Salmon and Hamilton and Buhl (1990) performed acute toxicity testing with juvenile salmon (9-13 wks and 18-21 wks), and in both cases, chromate had the lowest toxicity of the nine metals tested.

In this section we briefly summarize studies on the effects of chromium on Chinook salmon (or salmon generally), and describe and discuss in detail studies from two main research groups (PNNL and USGS). These studies are most relevant because they deal with hexavalent chromium and Chinook Salmon under well-controlled and well-described conditions.

Chronic effects of chromium in fish involve a wide range of systems. Reproduction and larval survival are considered the most sensitive stages (Holdway 1988), while histopathologic changes, hematologic changes, enzyme inhibition, neoplasia, as well as impaired locomotion are can also occur. Immune responses of fish may be affected by short-term exposure to waterborne hexavalent chromium (Sugatt, 1980a).

Acute Toxicology Studies

Historically, most aquatic toxicology studies used the median lethal concentration, the concentration which killed 50% of the individuals (LC50) as the endpoint of interest. The typical duration was 96 hours. In many acute studies the lowest concentration tested exceeded 1000 µg/L (=1 ppm). Trama and Benoit (1960) examined median or minimum lethal concentration with acute exposures of sunfish to Cr-VI. Holdway (1988 in Nriagu & Nieboer) summarized information on chromium toxicity to fish from both acute and chronic studies (including Cr-III as well as Cr-VI). Holdway tabulated results from more than twenty acute exposure studies of Cr-VI mainly reporting 96 hour lethal concentrations for 50% (LC50) in a variety of freshwater, and a few salt water fish. In general the LC-50 concentrations were >20,000 µg/L (=20 ppm), and in many systems > 100,000 µg/L. Rainbow Trout fry showed "no effect" at 14,000 µg/L after 96 hr. Year old Rainbow Trout had an LC50 of 69,000 µg/L. Eisler (2000) reviewed chromium hazards to fish and invertebrates. As a general rule it appears that acute toxicity thresholds are all in the part per million range (i.e. greater than 1000 µg/L). The ratio of the acute threshold versus the chronic threshold are particularly great for salmonid fish (EPA 1984). We did not consider studies where the exposure concentrations exceeded 1000 µg/L (1 ppm).

Although the LC50 (median lethal concentration) was once widely used as a standard ecotoxicology paradigm, it actually provided limited value in ecological risk assessment where even a 1% mortality (LC1 or toxicant threshold concentration) is now considered meaningful (Birge and Cassidy 1983). For example, a Rainbow Trout study of embryo-larval stages (from fertilization to hatching=28 days), found the LC1 of 22 µg/L (22 ppb) versus the LC50 in the same study of 190 µg/L. This relationship is not constant or linear, but in general an LC1 may be about an order of magnitude lower than the corresponding LC50.

Early Studies with Salmon

Although there are many papers on fish bioassays with either Cr-III or Cr-VI, few deal specifically with Chinook Salmon, although the congeneric Rainbow Trout is a popular assay species. Many papers use only the inclusive term "juvenile" which could refer to alevin, fry, or parr, while others provide information on age (weeks) or length of the fish studied. Olson and Foster (1956) had reported increased mortality of Fall Chinook exposed from eyed egg through swim-up at 77 µg/L for 100 days post hatch or at 180 µg/L chromium for 55 days. Sauter et al (1976) exposed Rainbow Trout eggs and fry to chromium (compound not specified) at measured concentrations of 51 to 822 µg/L. Hatching and 30 day survival were not reduced at the highest dose, but by 60 days weight of fry was significantly reduced at 105 µg/L. They calculated a maximum acceptable toxicant concentration (MATC) between 51 and 105 µg/L. As bioassay research evolved, the importance of careful controls on dissolved oxygen, temperature, pH, and photoperiod were augmented by attention to hardness, dissolved solids, and organic matter. This is particularly true for chromium which is influenced by hardness, pH changes and redox conditions.

Like Chinook, juvenile Coho Salmon *Oncorhynchus kisutch*, migrate to the sea and must quickly adapt to saline conditions. After exposure in a fresh water experiment to sodium dichromate, survival in salt water was significantly decreased in fish exposed to 230 μg/L of chromium for only 4 weeks or to 500 μg/L for only two weeks (Sugatt 1980b).

PNNL & USGS Studies with Chinook Salmon

Important, elegantly designed and well-controlled studies were conducted by Pacific Northwest National Laboratory and by U.S. Geologic Service scientists. The former (PNNL) studied effects of exposure during egg development and the alevin stages (Patton et al. 2001, 2007). The latter (USGS) examined effects on fertilization and hatching (Farag 2006a) and on growth and survival of free-swimming juveniles in the parr stage (Farag 2006b). The Patton and Farag studies were "part of an overall effort to evaluate the potential impacts of contaminated groundwater from the Hanford Site on fall Chinook Salmon populations" (Patton et al. 2001, p.2). The Patton and Farag researches were conducted in the 1998-2000 time frame. These studies used concentrations up to 266 μg/L or parts per billion (ppb), equivalent to about 5 micro-molar concentration (chromium molecular weight is 52). The results are somewhat conflicting and to this date remain incomplete with regard to chromium and Columbia River salmon (Gochfeld and Burger 2014). The Farag et al. (2006b) study has been criticized for changing doses in mid-study. Although this makes some interpretation difficult, it is a reasonable range-finding approach, after seeing minimal effects at 105 days at her original doses, and we include her results as she reported them.

Dauble et al. (2003b) provided a detailed review of chromium contamination at Hanford, and a detailed context for the Hanford Reach and Chinook Salmon life history, as a backdrop for summarizing toxicity tests conducted up to 2002, including the aforementioned Farag and Patton studies which were published subsequently. Some of the papers mentioned below, and published subsequently, were included in the Dauble et al. review. Dauble et al. (2003) concluded that "Overall, the results of both studies reveal that salmon exposed to aqueous chromium to 266 μg/L during the eyed egg to swim-up portion of their life cycle were not adversely impacted" (Dauble et al. 2003:5.4) and "a dose-dependent response for selected health endpoints of juvenile fish was corroborated with tissue concentration. DNA damage, lipid peroxidation, and death of the kidney cells occurred simultaneously as a result of chromium exposure" (Dauble et al. 2003b:5.8), at concentrations of ≥ 120 μg/L.

Farag et al. (2006a) found no reduction in fertility or hatching for eggs exposed to 266 μg/L of Cr-VI from fertilization through the point of "hardening". Farag et al (2006b) is the peer-reviewed, published version of the study referenced by Dauble et al. (2003b). Farag et al. (2006b) found no reduction in growth or survival after 105 days of exposure at 24 μg/L or 54 μg/L. At that point concentrations were increased from 24 to 120 μg/L (24/120 group) and from 54 to 266 μg/L (54/266 group) for an additional 29 days. The survival was somewhat reduced in the 24/120 group and significantly reduced in the 54/266 group. Weight was reduced in the 24/120 but not in the 54/266 group. Chromium concentration in tissues increased mainly in the gills and kidney. Biological and statistically significant tubular and interstitial kidney damage were seen in both the 24/120 and 54/266 groups. Some other histological changes were seen but were not consistently dose related. Nuclear content of DNA, assessed by the coefficient of variation difference between groups, was interpreted as evidence of "damage" after 105 days at 24 μg/L and 54 μg/L, but this finding is of uncertain significance and is not considered a LOAEL.

By contrast, the Patton et al. (2007) study (also referenced in Dauble et al. 2003b), found only slight, probably non-significant growth reduction at ≥ 49 µg/L, with no effects on survival, for fish exposed to Cr-VI from diluted Hanford groundwater with Cr-VI concentration up to 266 µg/L. We examined these two studies in detail (Table 4).

For their study of the egg/alevin stage Patton et al. (2007) exposure ran from the eyed eggs stage through the alevin stage to the median swim-up phase at 83 days. Alevin live off stored energy in their yolk sac for two or more weeks. Patton et al. (2007) continued observations of unexposed fry for an additional 30 days. Farag et al. (2006b) began exposure at 60 days post-swim-up (about 30 days beyond the point at which the Patton et al. (2007) observations ceased.

Table 4. Comparison of the Farag et al. (2006b) and Patton et al. (2007) papers on hexavalent chromium exposure of early life stages of Chinook Salmon.

	Farag et al. 2006b USGS "off-site study"	**Patton et al 2007 PNNL "on-site study"**	**Issues and Questions**
Source of fish	McNenny Hatchery, Spearfish SD	Priest Rapids Hatchery, WA (eggs from fish from Hanford Reach)	Are these different genetic stocks with different exposure histories? Columbia R. fish had 50 yrs to evolve tolerance
Life stages dosed	parr stage, begin 60 days post swim-up, continue for 105 days at low concentration and 29 additional days at higher dose	begin exposure at eyed egg and end at swim-up, then observed for one month	Before swim-up the alevins do NOT feed, after swim-up the fry feed voraciously.
Source of chromium	dichromate added to well water & deionized water	Hanford groundwater* with >2000 µg/L of Cr, diluted with Columbia River water	Almost "pure" water versus natural water with many other constituents.
Dosages	0, 24, 54 µg/L for 105d then 0, 120 & 266 µg/L for 30 d	11,24,54,120 & 266µg/L for 98 d then kept in River water to 132 d (but did not dose after 98 d)	Farag increased doses on day 105 because of no gross effects at 24 & 54 µg/L.
water hardness	76-86 mg/L as $CaCO_3$	35-87 mg/L as $CaCO_3$	Essentially the same hardness. Cr toxicity is enhanced in softer water, hence could

	Farag et al. 2006b USGS “off-site study”	**Patton et al 2007 PNNL “on-site study”**	**Issues and Questions**
			have been worse in Patton study.
water pH	7.6-8.0	7.0-8.0	Similar
Temperature	9.9-11.8C	5.4-5.6 C	Temperature could be a significant variable.
Conductivity Alkalinity Oxygen	166-180 µS/cm 76-89 mg/L as $CaCO_3$ Oxygen not stated	124-211µS/cm 64-80 mg/L Oxygen 9.2-14 mg/L	Similar
Mortality or survival	No change at 54µg/L (105 d) Decline at 120 µg/L and significant decline at 266 µg/L at day 134	>98% survival for all groups >98% hatch >98% swim-up	significant difference in results for the different life stages
Growth (length, weight)	Slight Decline at 54 µg/L. Significant at 120 µg/L	slight growth reduction at 49, 100 & 266 µg/L	These results may be consistent.
DNA damage	nuclear DNA change of uncertain significance detectable at 24 µg/L		
Lipid peroxidation as evidence of oxidative stress	slight dose related increase in the kidney		
Histopathology	interstitial blood forming cells at reduced at 24 µg/L. Renal tubule damage at 120 µg/L		The effects of prior exposure confounds the interpretation of the higher doses.
Glycogen utilization	some decrease at 24 µg/L inconsistent		
Behavioral toxicity	Not reported	“no observable differences in behavior (e.g., feeding patterns, startle response, schooling behavior, and response to light.”	

*Groundwater used from Hanford contained chromium at 2037-2980 µg/L

The differing outcomes of the Farag and Patton studies reflect different methodological approaches. There seems to have been little published comparison results (Gochfeld and Burger, 2014). Farag et al. (2006b) found no apparent growth or survival differences at either 24 or 54 µg/L after 105 days, but then after dosage was increased from 24 to 120 for an additional 29 days (to day 134), growth was reduced, while the 54/266 group showed significantly decreased survival by day 134. Whether the prior 105 days of low dose exposure contributed to the higher dose observations, whether they were a necessary "priming" dose is unclear, and warrants further study. Farag et al. (2006b) examined fish at the end of the first exposure phase (day 105), which provided endpoints for the 24 and 54 µg/L exposure. They reported alterations in glycogen metabolism and nuclear DNA content of uncertain significance. Renal damage was evident in the 24/120 group as well as the 54/266 group.

One explanation for the difference in response of alevin and parr, is that juvenile salmon have greater sensitivity following swim-up or during a period of increased metabolism and maximum growth." Buhl and Hamilton (1991) had shown for three fish species, including Coho (=Silver) Salmon (*Oncorhynchus kisutch*) that the free-swimming juvenile fish were more susceptible to several metals including hexavalent chromium, than the alevin stage. The general trend for susceptibility to toxics is to decrease as organisms mature and complete the development of vulnerable organ systems. Although this appears reversed in the salmon, it probably reflects different exposure opportunity (life style vulnerability rather than susceptibility). Alevin derive energy by absorbing the yolk sac; they do not eat. Yolk contents are derived from the adult female's body, from food eaten during her oceanic existence (there is little or no feeding on the spawning run). Fry and parr eat voraciously and grow quickly (Farag et al. 2000). This could account for both different exposures and different vulnerability. Patton et al. (2007) terminated the chromium exposure when the fish were no longer in the gravel stage. They followed the free-swimming fish for an additional month, but did not find increased mortality. They terminated observations at an earlier stage than Farag et al. (2006b) began dosing (60 days after swim-up). A valuable feature of the Patton study are the data on chromium concentrations in the fish themselves. At each life stage there was a dose-dependent relationship, while the chromium concentrations (micrograms/gram) decreased as the fish grew.

In addition to the non-overlap in the dosing chronology, we note several other potential differences in study design (given below) which could explain the discrepancy in results. Thus in both cases, the strengths of the two studies offer several avenues for future research to clarify some basic issues in aquatic toxicology of chromium:

a) Source of the fish. Patton's breeding stock were from the Priest Rapids Hatchery, of Columbia River origin. This is a population that over a half century may have been selected for chromium resistance, By contrast, Farag et al. (2006a) state "The Chinook salmon from the McNenny Fish Hatchery … should have no history of pre-exposure to contaminants in the Hanford Reach of the Columbia River."

b) Patton used Hanford groundwater diluted with Columbia River water to simulate the local environment, while Farag et al. used chromate added to distilled water plus well water, to avoid confounding by other substances. Natural groundwater may have many other constituents which could protect (or enhance) any effect of chromium. A protective substance, possibly the strong antioxidant effect of selenium, might confer protection in natural water, but not in deionized water.

Both of these approaches are justified and complementary. We conclude, based on these two studies, supplemented by others, that detectable effects on salmon parr occur with chronic exposure to as low as 24 µg/L. For free-swimming fish, significant toxicity which may impair survival occurs around 120 µg/L and possibly as low as 50 µg/L or at 77 µg/L (Olson & Foster 1956). However, these values are not necessarily relevant to Hanford and juvenile salmon in the Columbia River. If the non-feeding, pre-swim-up, alevin stage which stays in the gravel for several weeks, is not susceptible to chromium, then the elevated concentrations of hexavalent chromium in the pore water would not have an impact on survival, except in the small percent of samples that exceed 266 µg/L. This is demonstrated in the Patton et al. (2007) paper. Conversely, since the chromium concentrations in the river itself are very low (below 10 µg/L), a NOEC of 120 µg/L or even 50 µg/L for free-swimming fish, would not be relevant.

Tiller et al. (2004) found no detectable chromium (i.e. less than 10 µg/L) in Columbia River water, and no difference in the chromium content of juvenile Chinook Salmon collected upriver from Hanford and along the Hanford Reach. This indicates that the relative susceptibility of free-swimming juvenile salmon to chromium is less relevant in a water body with negligible amounts of chromium. But this does not address the alevin or very first days of swim-up when fry may still be at the interface between pore water and the Columbia River (Farag et al. 2000).

There is no single chromium concentration, above which one can confidently predict that any or all Columbia River salmon populations would decline. The research makes it clear that uncontrollable factors such as global climate and local weather, and controllable factors such as water management and fishing, have much clearer impacts on salmon survival and spawning recruitment (number of adults returning), and are likely to mask any toxic impacts directly on salmon at the low concentrations that occur in the Columbia River. Moreover, salmon of the Columbia are part of a complex ecosystem, the integrity of which is essential to support the salmon as juveniles. For the life phases of salmon living close to pore water in the gravel, a level below 24 µg/L is unlikely to be harmful, and the almost instantaneous dilution of groundwater as it escapes into the river, makes chromium impacts on free-swimming salmon, very unlikely as well. If the young fish spend time in backwaters or channels remaining close to the substrate, it is essential to measure the local levels of chromium to make sure there are no hotspots with high chromium levels.

Chromium Levels in Biota and Pore Water in the Hanford Reach

Considerable attention has been devoted to monitoring contaminants on the Hanford Site, and contaminants in sediment, pore water and biota in the Columbia River, but the relevant samples, specifically chromium concentrations in spawning areas (redds), are limited. Understanding potential exposure of salmon to chromium (or other contaminants) requires a complex sampling plan that examines spatial and temporal variations in chromium (especially in pore water). Chromium levels can be measured in pore water, in upwellings and seeps close to the redds, and in the water column of the Columbia River in the Hanford Reach, as well as in biota.

The *Draft River Corridor Baseline Risk Assessment* (RCBRA) (DOE 2011a) is the most recent and complex ecological risk assessment that collected samples from biota, as well as sediment and pore water from the Columbia River. The representative near-shore receptors were plants, insects, other benthic and aquatic invertebrates, amphibians, fish, birds and mammals.

The fish considered were sucker, sculpin, juvenile and adult salmon, and sturgeon (DOE 2011, page 6-5). However, the fish actually sampled for contaminant and histopathology analysis were sculpin and juvenile suckers (DOE 2011, p 6-24). Eggs and alevins were not sampled, nor were any juvenile or adult salmon. The following contaminants were measured: 36 inorganic chemical analytes, PCBs, pesticides or semivolatile organics, and 25 radionuclide analytes (DOE 2011, p 6-51).

RCBRA pore water samples were collected at 13 aquatic sites at a depth 10-15 cm (4-6 in) below the riverbed and allowed to settle for 15 days before sampling (WCH-274, p. 2-31). In a summary of risk characterization results and uncertainties for all fish, the list of contaminants of potential concern included hexavalent chromium, based on exposure evaluations from 17 pore/seep study sites and gradient analyses for 15 pore water study sites (all but 100B/C pilot and 100-NR-2 study sites). Hexavalent chromium concentrations in pore water samples exceeded the Washington State standards (chronic 10 μg/L and acute 15 μg/L) at five study sites as illustrated in Figure 16 (DOE 2011a, p. 8-56 and 8-57):

- 24 and 42 μg/L at aquatic site Cr1 near 100-K,
- 25 μg/L at aquatic site Cr2 also near 100-K,
- 15 and 21 μg/L at aquatic site Cr6 near 100-D,
- 24 μg/L at aquatic site 2a near 100-B/C, and
- 13 μg/L at aquatic site 2b near 100-B/C.

The report concludes that "there are pore water concentrations at which effects on fish might be expected to occur" (DOE 2011, p 6-119), but the report does not specifically refer to salmon.

Previous pore water samples were collected as part of two field investigations of sites in the Hanford Reach (BHI-00345, Rev. 0; BHI-00778, Rev. 0) as well as a study to support the Remedial Investigation (RI) of Hanford Site Releases to the Columbia River (WCH-380, Rev. 1). The field studies evaluated a new methodology (at the time) for collecting groundwater samples from the aquifer along the Columbia River shoreline. Verifiable pore samples were collected 20-31 cm (8-12 in) below the riverbed surface as part of the RI field investigation (WCH-380, Rev. 1, p. ES-1). Measured concentrations of hexavalent chromium in the pore water along the 100 Areas average less than 23 μg/L although individual measurements were as high as 632 μg/L. About 47% of samples (n= 284) had detectable hexavalent chromium (above the practical quantification level of 3.7 μg/L). About 25% of the measurements exceeded the Washington State chronic exposure standard of 10 μg/L. A small percentage of the pore water samples from these studies exceeded 100 μg/L (Table 5).

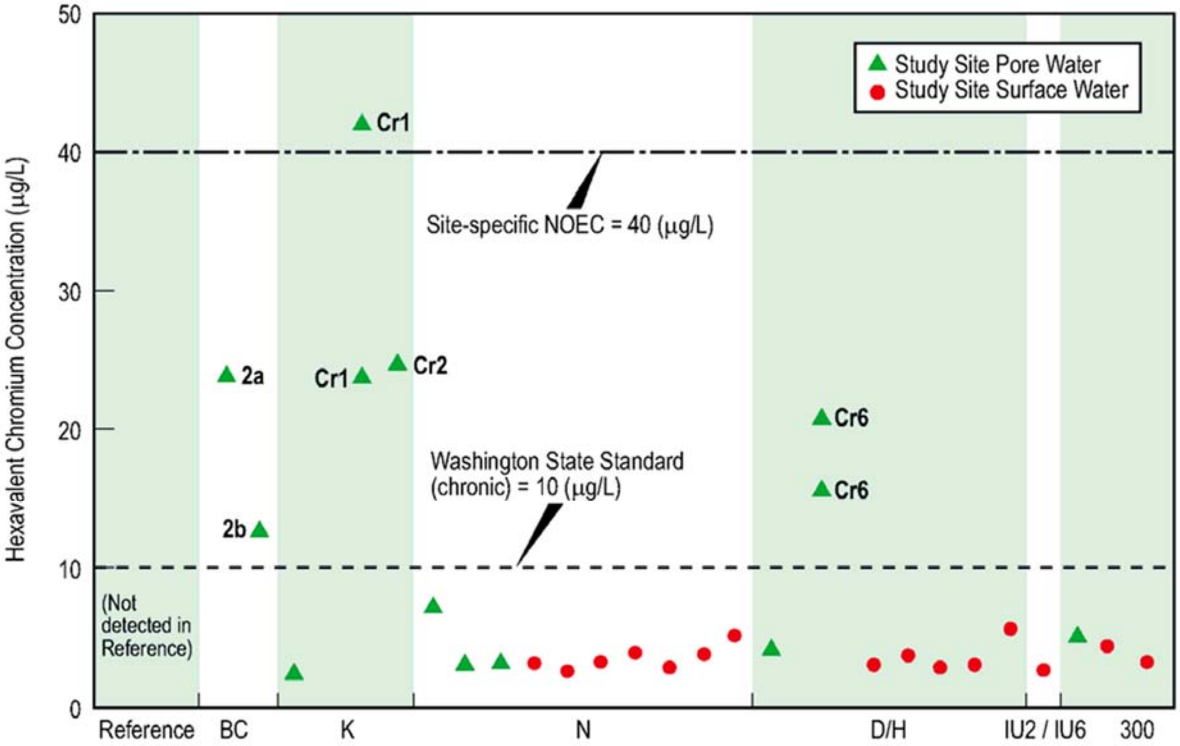

Fig. 16. Measured Hexavalent Chromium Water Concentrations for RCBRA Reference and Study Sites (DOE 2011a, p. 8-57). X-axis represents reference, reactor and 300-Area from upriver (left) to downriver (right).

Chromium levels in the pore water relative to demonstrated effects levels on eggs and alevins are most important because salmon eggs and alevins are stationary in the redds for several months (see Figs. 2, 3, 5). However, laboratory experiments have shown that the fry are more sensitive (or at least have more exposure potential) making it critical to measure chromium in the interface of the redds with gravel and the Columbia River. Ideally, chromium levels would be measured in pore water in the places where redds are located, but the pore water sampling locations were generally not selected to coincide with salmon spawning, and only some of the pore water samples were in spawning areas. Further, sampling could be conducted when there are salmon eggs and alevins in redds (DOE 2010). Although fry are free swimming, they may remain close to the substrate for protection and seek or be carried into backwater areas, and remain there for weeks (R. Buck, G. Bohnee, L. Greene, pers. comm.), where they could be exposed to contaminants through upwelling when they feed on the bottom. This possibility, however, may be small and needs to be investigated, particularly in relation to other causes of fry mortality, such as stranding because of water fluctuations or predation.

Table 5. Levels of hexavalent chromium in pore water by operable unit from the BHI-00345 (1995) and BHI-00778 (1996) for the 100-H and 100-D areas, respectively, and WCH-380, Rev. 1 (2010) in support of the Remedial Investigation. Sample sites were partly selected to reflect likely areas of upwelling, based on temperature and conductivity. Different sampling and analytic methods were employed in these studies. The total number of pore water samples in these two studies is 284. The maximum value is 632 µg/L(100-D Area).

Hexavalent Chromium (ug/L)													
				Gaussian			lognormal[a]						
Area	Year	Total N	Max	Mean	St Dev	Upper 95%	Mean	Upper 95%	PQL[b]	< PQL	% < PQL	Method[c]	Reference
100-B/C	2009	29	112	22.3	30.4	33.9	8.5	14.9	3.7	12	41.4%	EPA 7196A	WCH-380, Rev. 1 (2010)
100-D	2009	31	331	21.1	60.9	43.4	5.6	9.3	3.7	16	51.6%	EPA 7196A	WCH-380, Rev. 1 (2010)
100-D	1995	108	632	21.8	89.4	38.9	1.0	1.5	varies	54	50.0%	PNNL AdSV	BHI-00778, Rev. 0 (1996)
100-F	2009	19	8	---	---	---	---	---	3.7	18	94.7%	EPA 7196A	WCH-380, Rev. 1 (2010)
100-H	2009	32	46	12.2	12	16.6	6.7	10.3	3.7	14	43.8%	EPA 7196A	WCH-380, Rev. 1 (2010)
100-H	1995	33	130	15.5	34.7	28.5	1.8	3.8	varies	17	51.5%	PNNL AdSV	BHI-00345, Rev. 0 (1995)
100-K	2009	32	44	7.8	10.5	11.6	4.0	5.9	3.7	20	62.5%	EPA 7196A	WCH-380, Rev. 1 (2010)
100-N	2009	no hexavalent chromium data											WCH-380, Rev. 1 (2010)

[a] A lognormal distribution is often assumed for measurements with high relative variation

[b] Practical Quantification Limit

[c] EPA Method 7196A was used for the 2009 pore water study (WCH-381, Rev. 1 2010). This method was not used in the 1995 studies. The PNNL Adsorption Stripping Voltammetry (AdSV) values were selected from the three methods used in the study.

Table 6. Hexavalent chromium in pore water as it relates to effect levels for eggs and alevins (NOAEL =260 µg/L, after Patton et al. 2007) and effects levels found for parr (24 µg/L, 54 µg/L,

and 120 µg/L, after Farag et al. 2006b). Although the latter are effects levels, they are not necessarily ecologically significant because the fry are not normally in pore water. For each value, the number of exceedances is given in parenthesis after the percent.

Area	**Sample Size**	**Maximum chromium µg/L**	**% exceeding NOAEL for eggs/alevins 260 µg/L**	**% exceeding LOAEL effects level for fry 120 µg/L**	**% exceeding possible LOAEL for parr 54 µg/L[a]**	**% exceeding LOEL for fry 24 µg/L[a]**
100-B/C (2011a)[b]	--[f]	24	--[f]	--[f]	--[f]	--[f]
100-B/C (2009)[c]	29	112	0.00% (0)	0.00% (0)	13.8% (4)	24.1% (7)
100-D (2011a)	--[f]	20	--[f]	--[f]	--[f]	--[f]
100-D (2009)[c]	31	331	3.22% (1)	3.22% (1)	6.44% (2)	12.9% (4)
100-D (1996)[d]	108	632	1.85% (2)	3.70% (4)	6.50% (7)	14.8% (16)
100-F (2011a)	None					
100-F (2009)[c]	19	8	0.00% (0)	0.00% (0)	0.00% (0)	0.00% (0)
100-H (2011a)	--[f]	20	--[f]	--[f]	--[f]	--[f]
100-H (2009)[c]	32	46	0.00% (0)	0.00% (0)	0.00% (0)	18.8% (6)
100-H (1995)[e]	33	130	0.00% (0)	3.03% (1)	9.09% (3)	15.5% (5)
100-K (2011a)	--[f]	42	--[f]	--[f]	--[f]	--[f]
100-K (2009) [c]	32	44	0.00% (0)	0.00% (0)	0.00% (0)	6.25% (2)
100-N (2011a)	--[f]	8	--[f]	--[f]	--[f]	--[f]
100-N (2009) [c]	None					
100 Areas (2011a all samples)[b]	71	42	0.00% (0)	0.00% (0)	0.00% (0)	5.63% (4)
TOTAL	n=355	Max=632	1% (3)	1.7% (6)	4.5% (16)	12% (44)

a. The effects observed at these levels may not be significant adverse effects.
b. DOE/RL-2007-21 (DOE 2011a) using EPA Method 7196A.
c. WCH-380, Rev. 1 (2010) using the EPA Method 7196A.
d. BHI-00778, Rev. 0 (1996) using the PNNL Adsorption Stripping Voltammetry (AdSV) method.
e. BHI-00345, Rev. 0 (1995) using the PNNL AdSV method.
f. Only summary data were provided in the RCBRA for the 100 Areas – measured values for specific areas were estimated from Figure 16 and totaled in the next to the bottom line.

The studies in the previous section showed that an acute NOAEL (NOEC) for Chinook Salmon fertilization and hatching of 266 µg/L (Farag et al. 2006a). The chronic NOEC for egg/alevin was also 266 µg/L (Patton et al. 2007). Because 266 (5 micromolar) was the highest concentration used in both studies, the effects levels might be much higher than 266 µg/L. Only 3 of the 355 pore samples were above 266 µg/L. No clear chronic NOEC has been established for fry or parr, but some DNA effects of uncertain significance were found at 24 µg/L which appears to be a LOEL. After 105 days at 54 µg/L a reduction in survival was observed, which was statistically significant in the 24/120 group. The 24/120 µg/L (LOAEL) showed significant adverse effects (renal damage and mortality) which can be identified as a LOAEL for parr (Farag et al. 2006b). However, the parr do not occupy the pore water where the exceedances occur, but may linger close to the gravel surface for protection (Farag et al. 2000). Thus, in Table 6 we use these values to determine the number of exceedances of possible biological significance. As with many toxicological studies, it is difficult to evaluate the significance of these effects levels on individual growth and survival, and even more difficult to identify an effect on salmon populations in the future, when mature adults return to the Reach to spawn. In total, 3 of 355 pore water samples (1%) exceeded 266 µg/L, 1.7% exceeded 120 µg/L, 4.5% exceeded 54 µg/L, and 12% exceeded 24 µg/L.

It is also useful to examine the spatial distribution of chromium levels measured in pore water (Figs. 17 and 18). The number of pore water samples taken in actual areas with redds is limited as is information on seasonal or yearly variation.

To evaluate potential effects on salmon from food chain bioaccumulation we examined the data on invertebrates presented in the *River Corridor Baseline Risk Assessment* (DOE 2011). In this report, species evaluated included algae and vascular plants, aquatic insects (larval forms, adults), other aquatic invertebrates (crayfish, snails, clams, mussels, amphibians (a toad), and fish (DOE 2011, p 6-5). There were no relationships between total chromium in aquatic invertebrate tissues and pore water concentrations (DOE 2011, p 6-101). Hexavalent chromium concentrations in pore water were greater than the state standard at five study sites (as high as 42 µg/L), and it was not detected at reference sites. The overall conclusions were that "because hexavalent chromium concentrations are greater than the Washington State standard, and pore water concentrations are statistically greater than reference, it is identified as a COEC (Contaminant of Environmental Concern) for further evaluation of development for aquatic plants." The Hanford Reach supports few vascular plants (Neitzel et al. 2005), but, periphyton is at the base of the food chain that leads to the invertebrates that salmon fry consume. The paucity of data on chromium in aquatic invertebrate tissue, makes it difficult to evaluate the food chain exposure of salmon. Thus, any conclusions about food chain effects await further study. We recommend that any future risk assessment for effects on salmon should include tissue samples from both salmon themselves (at different life stages), and also of their food base.

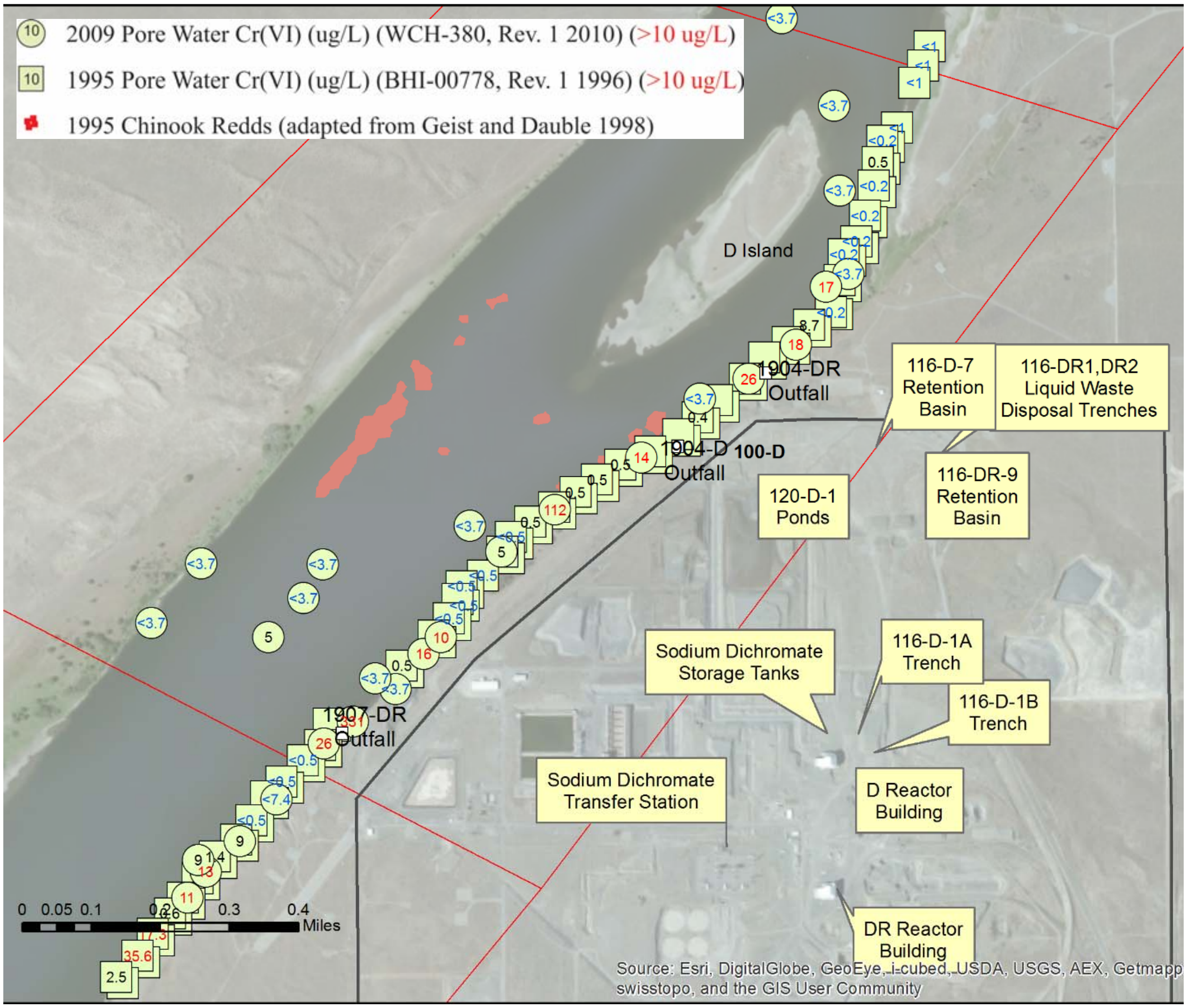

Figure 17. Map showing Chinook Salmon Redds (in red) and the Pore Water Sampling Locations (100-D, Area 8 on Figure 12) for hexavalent chromium (prepared by K. G. Brown). Concentrations above the Washington criterion of 10 µg/L are shown in red and those below the reportable limit (which varies by analytical method) are shown in blue.

Another question about hexavalent chromium concentrations and their relevance to the health and well-being of salmon relates to variations in chromium within the habitat of different life stages. For example, eggs and alevins are located in redds, which are three-dimensional nests within the gravel zone. Thus, there might be different levels of chromium at the top or bottom of the redds. The question of how the pore water is influenced by river water is relevant for salmon because the eggs and alevins are within gravel, which receives groundwater from upwellings through preferred pathways at the bottom of the gravel, and is washed by Columbia River water at the interface between the gravel and the river itself. Flow of Columbia River water within the redds is an important condition for necessary oxygenation during development. Under some conditions, the primary influence in the redds would be from groundwater upwellings, but under other conditions, river water could be exerting the greatest influence (Bunn et al. 2012). Under these conditions, the pressure of river water may suppress

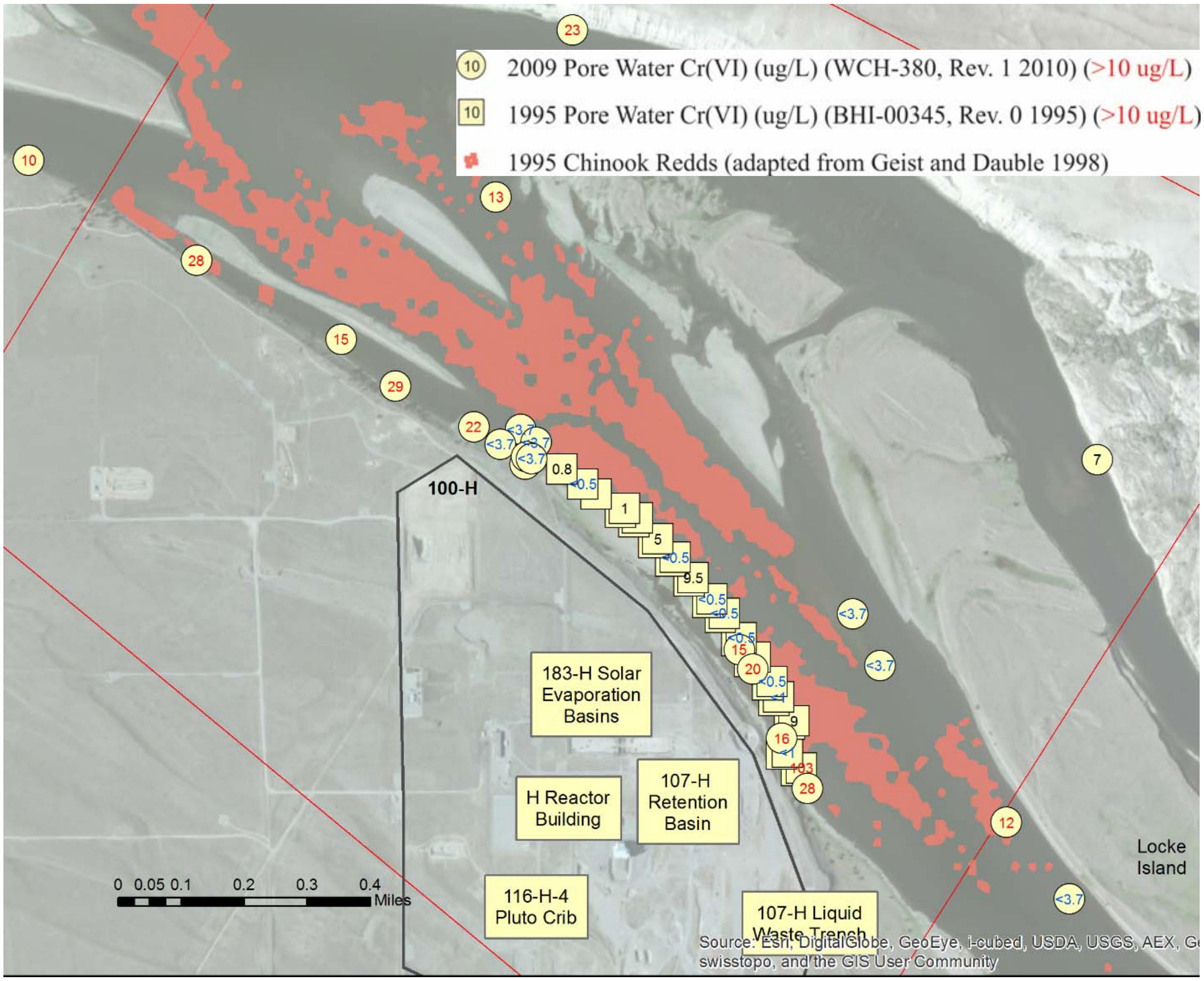

Figure 18. Map showing Chinook Salmon Redds (in red) and the Pore Water Sampling Locations (100-H, Area 5 on Figure 12) for hexavalent chromium (prepared by K. G. Brown). Concentrations above the Washington criterion of 10 µg/L are shown in red and those below the reportable limit (which varies by analytical method) are shown in blue. Redd distribution after Geist & Dauble 1998).

groundwater discharge (DOE 2011, p 6-36) although this interaction is complex (A. Bunn pers. Comm.). Under low river levels and low flows, groundwater discharges are relatively unimpeded, but when water levels are high and flow is great, groundwater has less of an effect on pore water in the gravel beds.

Evaluating Salmon Health in the Columbia River

One major assessment endpoint for the Columbia River is the health of salmon populations, particularly Fall Chinook. "Health" however, cannot be directly measured, and so measurement endpoints are required. Assessment and measurement endpoints can be used to: 1) assess current habitat, 2) set habitat, remediation, or restoration goals, 3) evaluate the efficacy of conservation, remediation or restoration projects, and 4) protect habitat for long-term population stability and sustainability. Species that move between different media, or different components within media types, have more complex habitat requirements than those that do not, and thus require more complex measurement endpoints.

There are a number of measurement endpoints that can be used to examine the "health" of salmon populations in the Columbia River. These include features of individuals and populations, and eventually the modeling of these factors. Individual characteristics include body size and weight (condition), time for different stages (e.g. egg, fry), age to maturity, time in freshwater/ocean, and reproductive parameters (clutch size, egg survival, fecundity). Population parameters include number of adult fish migrating upriver, number of redds, age structure, numbers of juveniles migrating downriver, ratio of males/females, and changes in populations. A readily available number is the number of adults observed passing each of the dams. Additionally, levels of toxic chemicals in salmon tissues, other biomarkers, growth and survival, physiology, and diseases or abnormalities are potential measurement endpoints, particularly for regulators, managers and others interested in environmental sustainability, remediation, and restoration.

Salmon have been subjected to a great deal of population modeling because of their economic, recreational, and cultural significance (Figure 19). For example, there are several American Indians tribes (Yakama, Nez Perce, Wanapum, and Umatilla) that have a traditional interest in salmon, and the Hanford Reach, one of the prime spawning areas (Dauble and Geist 2000). Salmon have been part of tribal culture for over 9,000 years (Landeen and Pinkham1999, Butler and O'Connor 2004). R. Buck (pers. comm, 2013) summarized the importance of salmon thus – "We catch salmon for a specific purpose for our culture and belief. We are worried, yes, but we need to eat salmon because it is who we are."

Many of the models for salmon have been developed to examine stock recruitment, escapement rates, and fish takes (Thompson and Lee (2002). Since hydrology, especially water depth and velocity, are critical to both sufficient oxygenation and protection of developing eggs, these factors have been modeled extensively, especially with respect to managing water flow from dams (Hatten et al. 2009). Tiffan et al. (2006) modeled the effect of habitat variables on juvenile fall Chinook salmon near the Hanford Site; important variables included temperature differences between the shoreline and the main river channel, mean velocities less than or equal to 45 cm/s, and juveniles concentrated near low lateral bank slopes, which provides relatively safe environments for foraging (fewer predators, lower velocity water).

Figure 19. Pow Wow and Salmon Feast in Idaho, where tribal members gather. Serving salmon is an integral part of their annual festival (photo by J. Burger).

Others have modeled the effects of different habitat characteristics on spawning (Connor et al. 1990, Geist et al. 2000), the presence of dams on spawning (Kareiva et al. 2000, Hatten et al. 2009) and effects on salmon survivorship (Honea et al. 2009).. Critical to these investigations is assessing the effects of present and historic habitats, determining which habitat changes have the greatest chance of increasing salmon populations, and protection of which life stage has the greatest potential to increase populations. The Honea et al. (2009) model indicated that population status could be improved by streambed restoration, with the reduction in the percentage of fine sediments. Models that combine the biological factors affecting population stability, and the physical factors that do so, will increase our understanding of options for management of viable Chinook salmon populations in the Columbia River and elsewhere. Further, dynamic rather than static models are required to accurately predict spawning activity (e.g. streamflow fluctuations over redds, Geist et al. 2008a). Models can also be used to estimate the success of re-introduction of salmon to river reaches currently blocked by dams with no passage, such as above the Chief Joseph Dam (Hanrahan et al. 2004).

Whereas most fishery models are aimed at determining sustainable harvest, population viability models (PVA) determine the probability that a fluctuating species population will fall to zero or some non-viable threshold (Medici and Desbiez 2012). PVAs have become popular in conservation biology to identify populations that are at risk of actual or functional extinction and to identify critical ecologic parameters. PVA estimates the probability of extinction, and allows prioritization of endangered species restoration. Viability analysis may help focus management activities on critical habitats or critical stages. It might be useful to develop PVA models for the different fish produced by different fish hatcheries to determine if a more natural hatchery environment (including predators) increases the viability of hatchery fish. PVA models may compare alternative management approaches to increase overall population size. This approach is used extensively in wildlife management, and is called "adaptive management."

Water Quality Criteria

The Washington State Ambient Surface Water Criteria for chromium is 10 μg/L (http://apps.leg.wa.gov?wac/default.aspx?cite=173-201A-240), which DOE is using as an applicable criterion for chromium remediation in the Hanford 100 Area, was developed from a set of bioindicators. Many of the bioindicator species may not occur in the Columbia River but may have ecological counterparts in the River. This criterion value may be lower than would be needed to be protective of salmon as the species of concern. However, this criteria may be appropriate because it was partly developed with invertebrate bioassays, and invertebrates are generally more sensitive to chromium than fish (Eisler 1986). When food chain implications are considered, chromium effects on invertebrates become important because juvenile salmon eat invertebrates (largely drifting aquatic insect larvae, such as midges, caddisflies and mayflies, Stanford et al. 2006, p 223). Moreover, many aquatic larvae develop in the sediment, where they would be in contact with pore water, allowing for bioaccumulation in the insect larvae, and subsequent food chain effects. Food chain effects have not been extensively examined. Tiller et al. (2002) found no difference in chromium concentrations in tissues of juvenile salmon in the Hanford Reach versus upriver from the 100 area.

There are also other applicable standards. EPA has posted National Recommended Water Quality Criteria "for protection of aquatic life and human health in surface water" (Table 7, EPA 2011). The freshwater levels of 11 and 16 µg/L are very close to the Washington values of 10 and 15 µg/L. In the table below, we also include saltwater criteria for comparison, which indicate that effects on organisms in freshwater occur at lower concentrations than those needed to produce effects in salt water.

Table 7. EPA Recommended Water Quality Criteria (µg/L=parts per billion).

Chromium	**Freshwater acute µg/L**	**Freshwater chronic µg/L**	**Saltwater acute µg/L**	**Saltwater chronic µg/L**
Trivalent (Cr-III)	570	74	---	---
Hexavalent (Cr-VI)	16	11	1100	50

Toxics, Chromium, Thresholds and Vulnerabilities.

For the DOE at the Hanford Site, state and federal regulators, Tribal governments, and others, understanding the role of chromium in impacting "healthy" and sustainable salmon populations is important. It affects decisions about the relative importance of controlling current chromium releases to the Hanford Reach, along with types and levels of Hanford remediation that may be needed to effectively remove chromium sources and reduce chromium entering the river. These would protect salmon, and maintain the Tribal, iconic, cultural, and economic importance of salmon to the Northwest, both now and in the future. While the regulatory requirement of 10 µg/L for hexavalent chromium is a surface water standard that DOE may choose to meet to comply with their state regulators, or choose to dispute, it is still important to understand whether this level is applicable to the river and the pore water within upwellings (which affect redds). And furthermore, it is critical to know whether salmon at various life stages are exposed to chromium at concentrations sufficient to cause chronic or acute effects. There are several measures of toxicity used by toxicologists in risk assessment. Detailed laboratory experiments are necessary to define each of these, and often the relevant experiments have not been conducted.

Much of the vulnerability of salmon to chromium depends upon the life stage, their habitat during that stage, and the length of time they spend in each habitat (see Fig.20), in addition to variability in the temporal and spatial patterns and interactions of chromium, and these all create uncertainties in determining vulnerability. Salmon lay their eggs in pockets in redds (nests) that are in gravel riverbed. Once laid the eggs imbibe water and "harden", and exposure is most likely during this phase. After about three months the eggs hatch into alevins, which remain in the gravel for several weeks. Once hardened, eggs are relatively self-contained, and after hatching the alevins rely on egg yolk remaining in their bodies to survive. Alevins do not eat, and thus are not exposed to chromium through ingestion. Once the alevins swim-up to the surface, they are called fry, and they begin to eat. Eggs and alevins are vulnerable to chromium and other contaminants only from the pore water in the gravel, while fry and parr also are exposed through the food and river water they consume or contact with their gills. There is uncertainty in the amount of time that alevins spend just below the river bottom surface (at the top of the redd in gravel), how much time the fry spend close to the interface, and when they enter the river stream (where there is negligible chromium due to dilution of pore water meets by river water).

Another uncertainty is in where and how the groundwater mixes with river water establishing a gradient of chromium as shown in Figure 20. This complex interaction depends upon the force and pressure of the upwelling groundwater and the force and pressure of the flowing river water (which in turn is a function of amount of water and flow patterns moderated by upstream dams, particularly Priest Rapids, A. Bunn pers. comm.). A final important data gap is the natural history of fry once they are swept from redds, and the time they spend in different habitats, including backwaters with potential upwellings, although levels of contaminants in such backwaters have not been documented.

As indicated in Table 8 below, there was no adverse effect on egg fertilization or hatchability at 266 µg/L, which is therefore a NOAEL for egg hatchability. However, the NOAEL for other stages is lower. We do not know whether the change in blood forming cells or nuclear content of DNA at 24 µg/L (Farag et al. 2006b, her Table 4 and Table 8) should be considered a LOAEL or LOEL. Patton et al (1977) found growth reduction that was not statistically significant at 49 µg/L, and therefore considered that this was not an "effect." A probable LOAEL for parr is 54 µg/L (Farag 2006b). The exposure at 24/120 µg/L produced multiple effects (mortality, kidney damage), and although the change in concentrations is difficult to interpret, the 120 µg/L can be accepted as a LOAEL for multiple endpoints for parr. Whether parr ever encounter these levels is unknown, as Tiller et al. (2002) found that river water did not have chromium at detectable levels.

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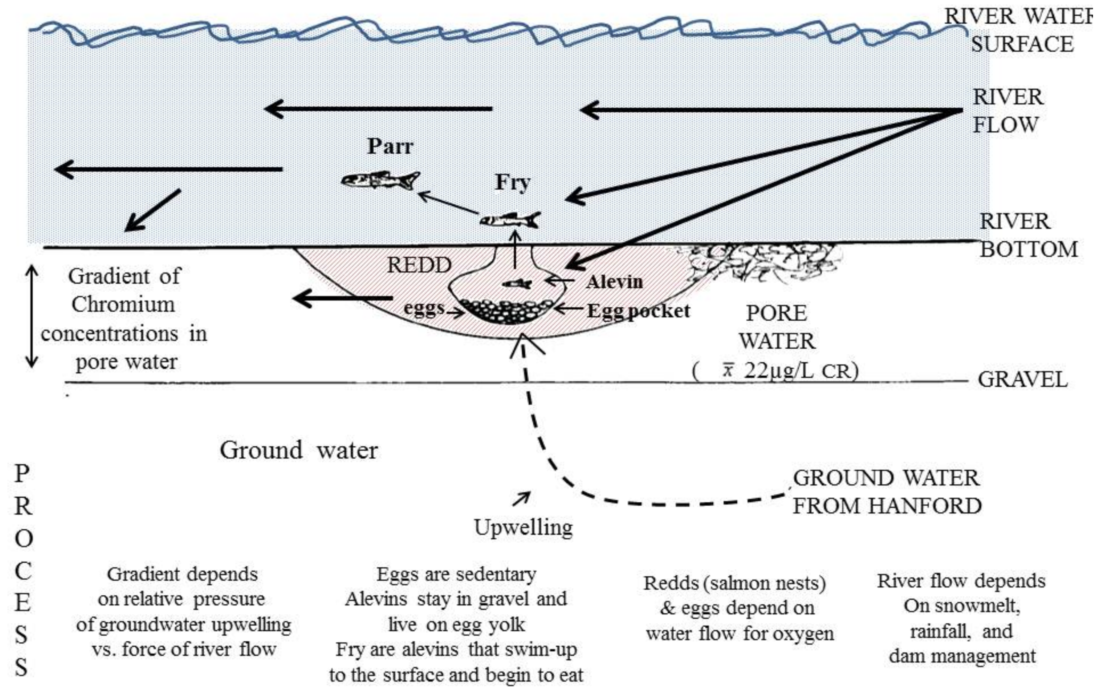

Figure 20. Schematic of the Vulnerability of Salmon on Redds, and the Processes that Affect their Vulnerability.

Although it is complicated to determine the NOEL, LOEL, and significant population effects because the experiments used many different exposure levels, exposure times, salmon life stages, and endpoints, these data can be summarized as follows (using only statistically significant differences):

Eggs in redds: No effects on fertility and viability to hatching with a brief exposure of 266 µg/L (= NOAEL, Farag et al 2006)

Alevins in gravel (redds): No significant effect at 266 µg/L (= NOEL, Patton et al. 2007)

Parr in river water: DNA effects of uncertain significance at 24 µg/L for 105 d Farag et al 2006b)

Parr in river water: Metabolic effects at 54 **(**µg/L (a possible LOAEL, Farag et al. 2006)

Parr in river water: Survival after 105 days at 24 and 29 days at 120 µg/L. A significant effect level.

Thus, the importance of chromium levels in salmon, given the LOAELs and NOAELs so far identified (from above and Table 8) indicates wide variation for different life stages (for some endpoints). However, risk assessment takes into account exposure assessment as well as toxicity. Thus these NOAELs and LOAELs must be considered in the light of three important factors: 1) what would happen when juvenile salmon are exposed in the Columbia River, given the exposure concentrations (in time and space), 2) where are the salmon at each life stage (temporally and spatially with respect to the river flow and levels, and chromium exposure), and 3) what is the duration of the exposures on different life stages (along with the duration of high concentration exposures).

Table 8. Comparisons of chromium criteria standards, and toxicity levels.

Human Health standards and criteria	**Chromium concentration** (µg/L)	**Environmental standards and criteria (Cr-VI unless otherwise stated)**	**Sources of Information**	**Comments**
California Public Health Goal for DW	0.02		http://www.cdph.ca.gov/certlic/drinkingwater/Pages/Chromium6.aspx (based on assumption that Cr-VI is carcinogenic by ingestion	Proposal for DW standard
NJ Risk based goal for drinking water	0.03		Source: Dr. Alan Stern (NJDEP) based on assumption that Cr-VI is carcinogenic by ingestion	
	10	Washington Surface Water Standard (chronic)	State of Washington Water Quality Standards Chapter 173-201A	Chapter 173-201A WACX Adopted by Hanford as an ARAR
	11	EPA Ambient freshwater quality criteria (chronic)	EPA 1980, updated 1986, 1995. The 1980 report included the documentation on which the criteria of 11 (chronic) and 16 (acute) were established	
	15	Washington Surface Water Standard (acute)		Water quality standards for surface waters of the

Human Health standards and criteria	**Chromium concentration** (µg/L)	**Environmental standards and criteria (Cr-VI unless otherwise stated)**	**Sources of Information**	**Comments**
				State of Washington
	16	EPA Ambient freshwater quality criteria (acute)		
	24	Chinook fry (LOEL & LOAEL)	Farag et al 2006 reported gill swelling, cell death, and reduced interstitial blood-forming cells in kidney and reduced energy use.	
	48	Washington	Ground Water, Method B, Non-carcinogen, Standard Formula Value (µg/L) (48 ug/l) (From CLARC)(A.Buchan email)	
	49	Chinook alevins (LOEL)	Patton et al. found slight, about 8% lower weights at 49 & higher doses (not statistically significant).non-significant growth reduction.	
California Drinking Water standard	50	EPA saltwater chronic Washington Model Toxics	Washington Model Toxics Control Act https://fortress.wa.gov/ecy/publications/publications/9406.pdf	
	54	Chinook fry ('parr')LOAEL	Farag et al. 2006 reported metabolic changes	
	74	Cr III	EPA Freshwater chronic	

Parr in river water: Metabolic effects at 54 (µg/L (= NOAEL, Farag et al. 2006)

Uncertainties and Data Gaps in Evaluating Future Risks to Salmon Populations and Chromium

There are several uncertainties when evaluating the risk to salmon in the Hanford Reach of the Columbia River. These uncertainties are of four types: 1) uncertainties in natural variation in parameters of salmon life history and breeding behavior (including food chain effects), 2) uncertainties in natural variation in weather, climate and geological events that impact salmon directly, or their habitat, 3) uncertainties in anthropogenic effects, and 4) uncertainties in measurements (experimental/observational, analytical), both in the capabilities of measurement endpoints, and in the execution of measurements. The types of uncertainties are summarized in Table 9.

Table 9. Types of Uncertainties Leading to Difficulties in Defining No Observed Adverse Effects Levels (NOAEL), Lowest Observable Effects Levels (LOAEL), and Thresholds for Chromium in Salmon. These are examples we developed from the literature (see reference section generally) and our own work.

Type of Uncertainty	Examples
Natural Variation in Salmon Life History and Breeding Behavior	-Yearly differences in breeding cycles, timing of migration and spawning -Individual and population variations in breeding cycles, timing of migration and spawning -Yearly and individual variations in habitat use -Variations in susceptibility to contaminants, temperature and other environmental variables -Individual and population variations in ability to use fish ladder, or negotiate dams (upward or seaward migration) -Individual and population variations in fish mobility at different life stages -Individual and population variations in spawning adult mobility among possible spawning areas between dams (e.g. salmon can move upstream and spawn where they stop, or move back and forth among spawning areas (even in different inter-dam regions).
Natural variation in weather, climate and geological events that impact salmon directly, or their habitat	-Daily, seasonal and annual changes in rainfall, snowfall, and temperature. -Global changes in rainfall, snowfall, and temperature -Changes from El Niño and La Niña cycles that affect ocean conditions where salmon spend most of their lives -Episodic events such as earthquakes, volcanoes
Variation in anthropogenic effects	-Differences in management practices for dams, mining operations, industrial and agricultural development; DOE remediation impacts on habitat, hydroelectric dam-caused differences in water flow in Columbia River

Type of Uncertainty	Examples
	-Increased residential or agricultural development, run-off and sediment discharge into the Columbia River -Differences or changes in fisheries practices, including recreational and commercial harvest, hatchery production, fish ladder, and contaminant loads entering the river.
Variations in Measurements	-Detection level for field and laboratory measurements -Yearly improvement in laboratory detection limits -Variation in technician efficacy with instrumentation -Variation in field observations -Differences with counts at dams (from dam to dam, from year to year, and using the same methodology -Individual differences in human abilities to count (redds, for example), and problems with aerial counts (turbidity and clarity affect aerial counts) -Current limitations for counting migratory salmon, and variations among estimation techniques -Variation in laboratory bioassays precludes exact comparisons

These uncertainties are partly a function of data gaps with respect to the biology and life history of salmon, chromium levels in pore water and river water, toxic effects of chromium on different life stages, and the relative protectiveness of regulatory standards. Further understanding of the biology of salmon is critical. Questions that specifically need to be addressed deal with length of time different life stages spend in different habitats (e.g. gravel, gravel-river interface, in the river; shallow vs deep water, main part of the river vs backwater areas). Both means and variances are essential to understand potential population effects. That is, what percent of a population (for each life stage) lives in the gravel/river interface, or what percent of the population spends time in shallow water where seeps may have a greater effect on water quality?

As is evident from the above table, uncertainties can include both data gaps, variability (e.g. in natural systems or organisms), and irreducible uncertainty (things that are unknowable). Some data gaps can be filled with sufficient ingenuity, time, personnel and money. Some data gaps relate to the effectiveness of chromium containment and chemical barriers (OHWB 2002). These include the effectiveness of pump and treat in reducing chromium movement, and what happens if pump and treat is stopped? Potential changes in chromium plumes and chromium entry into the Columbia River (through seeps, upwellings, run-off, and sedimentation) should also be explicitly measured and modeled. Also uncertain is how closely aquarium-based studies predict survival, condition, migration, recruitment and reproduction under wild conditions with and without chromium.

Other data gaps less directly related to salmon, that indirectly affect salmon through changes in river conditions and physiognomy, also need to be filled. These include examining the effects from the "big dig" (to remove chromium sources in the 100 Area, French 2012), or other remediation options on sedimentation, chromium releases, and chromium entry into the Columbia River. Siltation and sedimentation have the potential to change water chemistry, clarity, and depth and flow, thereby changing habitat suitability for salmon.

There are data gaps in understanding the effects of chromium on the various life cycle stages of salmon (eggs, alevins, fry, parr, adults), for different endpoints from subtle behavioral effects that may not affect individual survival to death. Although the Farag (2006a,b) and Patton et al. (2007) answer some of the questions, others still remain. It should be noted that although these two studies were published in 2006 and 2007, the experiments were conducted in the late 1990s and were reported in Dauble et al. (2003b). Some data gaps relate to understanding the toxic effects of hexavalent chromium. These include more experimentation with different dosages, using river water laced with chromium levels that have been measured to correspond to pore water concentrations of the Columbia River bed (OHWB 2002). These experiments should be performed with eggs, alevins, and the first few weeks of fry. Further, the NOAEL has been determined for eggs and alevins (e.g. 266 µg/L), but the LOAEL has not been identified. That is, some hexavalent chromium levels higher than 266 have been found in pore water, thus the actual effects level for eggs and alevins needs to be determined by experimentation. There are also data gaps in our understanding of the relationship between individual effects and population effects. The toxic effects of chromium on salmon invertebrate prey are another critical aspect of understanding the food chain that leads to salmon. If the invertebrates that salmon eat are affected at specific levels that exist in pore water or the gravel/river interface, then this could have an indirect effect on juvenile salmon.

There are data gaps in understanding the relationship between various water quality criteria and their applicability to salmon in the Columbia River. The relationship of standards developed using free-swimming organisms to organisms that live part of their life cycle in pore water (e.g. salmon eggs and alevins) needs to be examined. This examination needs to include a food chain approach, with not only salmon as an endpoint, but higher trophic level fish, birds and mammals.

Salmon Populations and Management

Management of salmon has received considerable attention, focusing on fisheries management, harvest levels, hatchery production, and mainstem dams that block access to historic spawning habitat, cause downstream mortality, and change water flow (papers in Williams 2006), as well as by the state of Oregon (Dent et al. 2005) and Washington (Crawford 2007). Both states have provided indicators for improving the health of salmon and watersheds. Managing radionuclides and other contaminants is thought to be relatively unimportant by fisheries biologists (Stanford et al. 2006). Maintaining the Columbia River as a healthy ecosystem is an important goal for Tribes, U.S. federal and state governments (resource trustees and managers, regulators), and a wide range of other stakeholders. Salmon are ecological keystone species and iconic organisms within the system that provides cultural, aesthetic, economic, recreational, and "bioindicator" values. Salmon are integral to Tribal lifeways (Landeen and Pinkham 1999, Harris and Harper 2004, Ridolfi Inc. 2007, CRITFC 2013) with estimates of daily ingestion exceeding 300 g (Lambert 2008) thus protection of salmon populations is a key societal goal. Managers and scientists working with salmon generally agree that the key factors affecting the health of salmon populations are harvesting, hydropower management, hatchery supplementation, and habitat loss (NRC 1996, Dauble 2000, Groot and Margolis 2003, Williams 2006).

For DOE managers, Tribal leaders, state and federal regulators and others, preventing the flow of radionuclides, metals and other contaminants into the Columbia River is a primary goal at Hanford. Chromium has emerged as a contaminant of concern (COEC) with respect to salmon, and in this document we examined the factors that affect chronic toxicity, including salmon life history and life cycles, spatial and temporal patterns of spawning and development, habitat requirements, acute and chronic chromium toxicity data for salmon (and other fish), and the management implications of these factors. Other contaminants of concern in Columbia River salmon include DDT and PCBs (Lambert 2008).

Managing ecosystems to achieve sustainability of populations, communities and ecosystems is a complex task. Managers and the public want ecosystems to provide goods, services and cultural values on the local, regional and national scale. Requirements for conservation and preservation of one species may conflict with those of one or more other species, for example the conflict between salmon protection and seabird control at the Columbia River Estuary Decisions made for management of one species, may harm (or benefit) others.

For managers and regulators of the Hanford Site, one key Assessment Endpoint for a wide range of stakeholders is maintaining healthy populations of salmon, particularly Fall Chinook Salmon that spawn in the Hanford Reach. The issue discussed in this report is the health of salmon populations with respect to chromium contamination from the reactor areas, (Hanford 100 Area) which can be divided into six major questions:

1. What do the toxicity data tell us about chromium effects on salmon?
2. Are the toxicity data (and experiments) relevant to chromium in the Columbia River?
3. Are chromium releases sufficient to affect individual salmon in the Hanford Reach?
4. Are chromium levels high enough now (or could they be in the future) to adversely affect salmon populations?
5. Under what circumstances could chromium releases be high enough to cause problems now or in the future (when could sources increase to the river)?
6. What is the role of adverse effects of chromium on some individual juvenile salmon, and on salmon populations relative to other adverse population effects?

Given the data and observations presented in this report, we provide the following answers to these questions:

1. *What do the toxicity data tell us about chromium effects on salmon?* The toxicity data indicate that Chinook Salmon eggs and alevins are not affected by chromium levels of 266 µg/L; these stages occur in the redds, and experience groundwater upwelling chromium concentrations. The fry stage is the most vulnerable, with some effects detected at 24 µg/L, and possibly significant effects at about 50 µg/L; this stage occurs after swim-up, when the fish are unlikely to encounter such levels of chromium in the

river. The difference in vulnerability is likely due to the fact that eggs and alevins do not eat, while fry eat extensively and thus have opportunity for food chain exposure. As indicated, the behavior of fry requires further examination to determine the time they may spend in shallow, still water where upwellings might affect chromium levels.

2. *Are the toxicity data (and experiments) relevant to chromium in the Columbia River?* For some stakeholders chromium is a major contaminant of concern in the Hanford Reach of the Columbia River. Some of the apparent discrepancies in toxicity outcomes among studies are readily explainable by methodological differences. Patton et al. (2007) used a fish source from the Columbia River, reflecting a half century of Cr-VI exposure and possibly increased tolerance, and used Hanford groundwater diluted with Columbia River water which would have contained other constituents that might affect responses. Furthermore, Patton et al. focused on egg and alevin life stages. Farag etal.(2006b) used a purified system (no genetic tolerance and deionized water), to provide bounds on toxicity and focused on post-swim-up life stages. Thus, the two studies used different life stages with different exposure potential. Completing the picture with additional toxicology studies using cross-overs in design across all life stages from oocyte to parr, is desirable.

3. *Are chromium releases sufficient to affect individual salmon in the Hanford Reach?* Hexavalent chromium levels in pore water along the 100 area averaged less than 23 µg/L although they range as high as 632 µg/L. About 47% of samples (n= 284) have detectable chromium (above the practical quantification level of 3.7 µg/L. About 25% have levels above 10 µg/L. Less than 1% of pore water samples in the 100 Area and 3% in the 100-D area have exceeded 266 µg/L, the documented NOAEL for eggs and alevin. No pore water samples exceeded 266 µg/L in other areas sampled. Therefore, only a small percentage of salmon redds could encounter pore water concentrations > 266 µg/L, and since the effects level (LOEC) has not been identified, it is not known whether the maximum concentration of 632 µg/L would impact any of the eggs or alevin. Juvenile fish, for which effect levels have been established, are mainly in flowing water where Cr-VI levels are very low.

4. *Are chromium levels high enough now (or could they be in the future) to adversely affect salmon populations?* Hexavalent chromium levels could possibly be high enough at some times and locations to impact individual salmon, at different life stages, and could get higher if groundwater pump-and-treat remediation ceased prematurely. Chromium could, in the future, also be increased to adverse levels during removal of the reactors, removal of contaminated soil resulting in run-off into the river, or if other preferred pathways develop that could lead to higher concentrations in pore water at points of discharge to the Columbia River. The potential for increases in hexavalent chromium concentrations to be discharged to the Columbia River should be carefully evaluated within any remediation strategy (including the current ones). This suggests the need for a continued field monitoring program to track potential changes in chromium in the river and in fish tissue, in population dynamics, physiological/morphological endpoints, and in genetic endpoints for fish of concern (e.g. salmonids). Permanent pore water sampling sites could be established as “monitoring wells” to detect temporal variation and trends.

5. *Under what circumstances could chromium releases be high enough to cause problems (when could sources increase to the river)?* For ecologists and others interested in

Chinook Salmon (and other salmon), the key question is – Are the hexavalent chromium levels high enough to affect salmon populations (not just individuals)? The State of Washington has said "no" (Washington Dept. of Health, http://www.ecy.wa.gov/programs/nwp/salmon.html). In our estimation, given the toxicity data, effects levels, the magnitude of effects, and the current levels of chromium in pore water (that could affect eggs and alevins) and in the Columbia River water (that could affect fry, juveniles, and adults), there are likely no current or foreseeable effects on salmon populations. Some individuals could be adversely affected by the highest pore water concentrations in the riverbed (above 266 μg/L, which have only been observed in 3 percent or less of the measurements and only in the D Area, or if fry concentrate in backwaters and forage directly over upwellings (in the latter case, concentrations of chromium in such backwater upwellings have not been examined). However, there is evidence that salmonid fry can detect and avoid chromium. It is unlikely that Cr-VI in river water would exceed 10 μg/L, much less reach an effects level. However, we can envision situations in which individual fry might remain at the bottom near upwellings and experience some exposure to chromium, or if chromium levels increased substantially (see #4 above) such that salmon are affected, but this is not currently the case. The salmon's reproductive strategy is to produce several thousand of eggs, of which very few survive to reproduce (even in the absence of any pollution effects).

6. *What is the role of adverse effects of chromium on some individual juvenile salmon, and on salmon populations relative to other adverse population effects?* We have concluded that the current contribution of exposure to hexavalent chromium on Fall Chinook Salmon populations in the Columbia River (and the Hanford Reach) is very minor compared to the other stressors on salmon population, including dams (that impede movement to natal spawning areas and the downstream movement of juveniles, change river flow and volume), fisheries (that remove reproductive adults), hatchery production (that dilute native stock), predators (that remove juveniles), ocean productivity and competition among adult salmon and other species for food in the ocean, and upstream sources of pollutants from urbanization, industry, mining and agriculture. As Stanford et al (2006, p 211) noted, "water pollutants ….other than metals from metals from mining…generally are not considered a major factor in salmonid declines nor particularly problematic for recovery" although they note that critical habitats for all life stages have not been examined extensively. Further, the EPA wrote a *State of the River Report for Toxics* in 2009, and at that time, the contaminants of concern in the Columbia River they discussed did not include chromium but were mercury, DDT (and its breakdown products), PCBs, and PBDE flame retardants (EPA 2009). From a tribal perspective, Lambert (2008) emphasized DDT and PCBs, mentioning only that chromium, among other metals, has been measured in salmon. Further, in *Return to the River: Restoring Salmon to the Columbia River* (R.N. Williams, ed. 2006), pollution is only mentioned 4 times, chromium is not mentioned, and mining metals are the metals of concern. The emphasis in that volume is on returning the river to a normative river flow, as well as restoration measures dealing with dams and fisheries management.

In our estimation, the low levels of chromium in most pore water samples, and absence (non-detectable) of hexavalent chromium in Columbia River water in the Hanford Reach, in conjunction with the toxicity tests and experimentation indicate that there is an extremely low probability that hexavalent chromium from the Hanford Site is currently affecting any salmon, much less significantly effecting salmon population dynamics. We did not assess effects of chromium on benthic organisms, which if significant, could indirectly impact salmon. Ideally there should be no exposure to anthropogenic Cr-VI. The River and its ecosystems gain no benefits from it. This study did not examine other contaminants that may be present in pore water or the river or in salmon themselves, which could increase or reduce toxic effects of chromium or confer toxicity on their own.

Continued monitoring of chromium levels in upwellings/pore water is worthwhile, and additional characterization of chromium (and other contaminant) levels in areas of redds is desirable. If there are changes in the source that result in increased release of chromium to groundwater and the river (e.g. due to cessation of pump-and treat, establishment of new preferred pathways, reactor removal), chromium concentrations could reach effect levels for individuals, and possibly populations of salmon spawning in the Hanford Reach.

Conclusions and Recommendations

We concluded that: 1) Salmon are important cultural, economic, and symbolic species within the Columbia River Basin Ecosystem, and are particularly important for Native Americans, 2) Some members of tribes state that they must continue to eat salmon for cultural and health reasons, 3) Several species of salmon spend a significant part of their life cycle in the Columbia River Basin, 4) Salmon populations, particularly Fall Chinook Salmon, have increased over the past 50 years in the Hanford River, and spawning escapement has increased dramatically in the Hanford Reach, 5) up to 90% of the fall Chinook Salmon spawning in the central Columbia River did so in the Hanford Reach (until recently, when spawning has increased in the Snake River), 6) The primary factors affecting population levels of salmon in the Columbia River are harvesting, hydroelectric development interfering with upriver migration and affecting water flow, and hatchery production, 7) contaminants are not felt to be of major concern by fisheries biologists, 8) Hexavalent chromium is a contaminant of concern related to the Hanford site, and has been identified as the driver for clean-up in the Hanford Columbia River Corridor by some DOE officials, the Hanford Advisory Board, and others (River and Plateau Subcommittee, HAB webcast, January 2013), 9) Laboratory experiments on the effects of chromium on salmon indicate that a NOAEL for survival of eggs and alevins is 266 µg/L, and for fry it ranges between 24 and 120 µg/L, 10). The LOAEL or LOEC has not been determined. The low levels of chromium in most river bed pore water samples, and absence (non-detectable) of hexavalent chromium in Columbia River water in the Hanford Reach, indicate that there is an extremely low probability that hexavalent chromium from the Hanford Site is currently affecting any salmon populations, 11) continuation of groundwater pump and treat for interdiction of chromium plumes, reduces a source for chromium in the river, and 12) continued monitoring of chromium levels in upwellings and pore water is desirable (especially if there is a change in source), and new characterization of chromium levels in areas of redds is important.

APPENDIX A. Key Information for Salmon in the Columbia River

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
Scientific Name	*Oncorhynchus tshawytscha*	*O. nerka*	*O. kisutch*	*O. keta*	*O. mykiss*
Other Names[1]	King Salmon, Spring, Tyee,	Red Salmon Non-anadromous Sockeyes called Kokanee[38] Nerka, Blueback[40]	Silver Salmon Kisutch[43] -	Dog salmon	Anadramous (ocean-going) form of Rainbow Trout
Weight[1]	1.5 –30 kg	2.2-3.1 kg (max 6.3 kg)	1.3-14 kg	4.5-6.5 kg (max of 15 kg)	
LIFE HISTORY					
Lifespan	1-8 years[44]	2-4[44]	1-3[44]	3-5[38]	3-7, may be longer[44]
Life stages	Egg, alevin, fry, parr, smolt, adult	Egg, alevin, juvenile, adult	Egg, fry, smolts, juvenile, adult	Eggs, fry, juveniles, adults	Eggs, fry, adults, kelts; adults that have spawned and return to the sea[9]
Typical cycle	Fall run Lay eggs in fall, hatch in spring (3 mo), spend 1 year in freshwater before smolting and migrating to ocean[5]	Lay eggs in fall, hatch January to March, stay in gravel until March to May, most move to ocean the next spring, but others remain 2 or 3 years in freshwater, then go to ocean,	Lay eggs in fall, hatch in spring, migrate to sea in spring of second year[6] -	Spawn October – December, hatch and emerge from gravel, then move rapidly to the ocean, mature at 3-5 years (usually 4)[38]	They migrate to the sea throughout the year, at first or second year[9] Most adults return in late summer and early fall, and spawning occurs in late spring[7]

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
		mature 3-5 years[38]			
Age of 1st breeding	2-8 years, depending on run; some come back to breed at[15] -	2-4[43] 4-year olds[9] 3-5 years[38] -	2-3 years[44] 2 years as jacks[6,43] Fall of their third year[9] Most in their 3rd year[38,43]	3-5 years[8] 2-5 years, can be up to 7[43] -	2-3 years[9] Some up to 7[42] -
Density (nests or egg pockets) in suitable habitat	8.9-16.1 redds/ha[4]		Size of redds proportional to size of female, and inversely related to size of gravel[43]		
Fecundity (eggs laid per female)	4,200 to 5,900 eggs[7] 3,000-7,000 eggs[9] -	Average of 3,500 eggs[9] Each egg pocket 500-1,100 eggs, each female has 3-7 egg pockets[40]	3,000-4,000 eggs[9] Female might carry 5,000 eggs but deposit 1,527-3,600, average 800-900[43]	2,000-4,000 eggs -	200-9,000 eggs[9] 5,300-6,000 eggs[7] -
Survival data	34.1 % annual mortality for all age classes[42]	Only 17.4 % of age 2 smolt returned[40]	Survival from smolt to adult of 0.98-19.1%[43]	0.3-3.2%[41]	
2012 counts Priest Rapids[31]	Chinook 124,987 Jacks 13,500	408,258	Coho 8.381 Jacks 1,577		17,230 (no wild steelhead)
Types of runs	Spring, summer, fall	Late spring and early summer runs[36] Runs are May through August, spawn in fall[37] -	Late August to mid-November[37] Spawning November – January[43] -	Fall[8] -	All year, more in summer than winter[9] Main run summer and winter, both spawn in winter and spring[35]

Parameter	***Chinook**	**Sockeye**	***Coho**	***Chum**	***Steelhead**
RUNS – TIMING					
	Spring: Early spring, peaks in mid-May, enter upper Columbia tributaries from April to July. Spawning occurs in late summer (peak is mid-late August)[7] Spawning in the 1960s was late July to Late September[10]	May to August, and into September39	August – mid-November[38]	October through December[38]	Winter and summer[38] All year[9]
Summer run	Spawning from mid-August to mid-November[10] Late Chinook for the summer/fall run spawned in Hanford Reach, earlier ones went up to the upper Columbia[28]	Variation in when late summer fish leave estuary and enter river is dependent on reproductive development and hormones (may be 6 weeks earlier, Fraser River, BC[27]			Summer - steelhead overwinter in freshwater for 6-10 months prior to spring spawning[24] -
Fall run	Spawn September to December[10] Fry emerge spring[28]				
SPAWNING LOCATIONS (Columbia River)					

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
	Hanford Reach, and Wenatchee, Entiat, Methow, Okanogan[44]	Wenatchee, Okanogan[44]	Wenatchee, Entiat, Methow[44] May use lakes[6] -	Lower 300 km of Columbia River[41]	Upper reaches of watershed[9], Wenatchee, Entiat, Methow, Okanogan[44]
Spring run	Upper reaches of four tributaries[44,9]				
Summer run	Lower reaches of same tributaries, also main River[10,44]				
Fall run	Lower reaches of same tributaries, also main River[10,44] Most (82 %) redd clusters in Hanford Reach were between White Bluffs and 100F island complex[3]	Lake at the end of headwaters, or move directly to take from streams[9] -		There are October runs[41] -	
Redds	4 m x 8 m depression in gravel to bury eggs; clusters of nests were 0.3-52 ha[3] -	Egg pockets 15-23 cm below redd surface.	Eggs buried 17.3-39.1 cm (California)[43] -	About 20-40 cm deep; can range from 7.5-50 cm (many places)[41]	
SPAWNING HABITAT REQUIREMENTS					
		Redds mean width of 1.7 m, mean	Redds mean of 134 cm long, 112 cm		

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
		length of 2.3 m (area of 4 m^2)[44]-	wide, and 22 cm deep (Russia)[43] From several studies, average area of $1.5m^2$, [43]		
General		In lakes and tributaries of lakes[38] Spawning areas near their juvenile rearing lakes On shoal beaches along lakes in areas of upwelling groundwater to provide circulation, and spring-fed ponds, rivers between spawning areas, females can detect upwelling[40]	In small streams, mostly lower tributaries, a few middle watershed areas[38]-	In lower parts of tributaries that enter Columbia River below Dalles dam[38]-	In streams of all sizes[38]-
Pebble count, riverbed	Riverbed armoured[2] -	Mean of 67.3% gravel(BC)[44] -	85 % of nests where substrate was gravel 15 cm or smaller[43]		
Grain size	25-305 mm, No fine material[2] Mean of 29 – 47.1 mm	Use was greatest when substrate has less than 15	Pea to orange-size gravel[6] -	13 % gravel larger than 15 cm, 81 % 15 cm or less, 6 %	

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
	(California)[17] 2.5-15.0 cm (Snake River)[39]	% fine sediment[44] -		silt in Columbia R.[41]	
Fine sediment size	Mean of sediment > 2mm diameter surrounding egg pocket was 5.7 - 8.7%[17]	Mean substrate composition 21.3% fine[45] -		Survival highest in gravel containing 11-30% sand[41]	
Water depth	0.30-9.5 m^2 2-4 m^4 0.2-6.5 m[39]	3-4 m, water depth not critical[40] -	Average of 18 cm over redd[43] -	13.4-49.7 cm[41] -	
Water velocity (water column)	0.23-2.25m/s[2] Greater than 1m/s[3] 1.4-2m/s[4] 0.4-2.1m/s[39]		5.0-6.8 m^3/min (Washington) ; Mean of 0.58m/s (California)[43]	80% spawned at 21.3 – 83.8 cm/s (Wash)[41] -	
Water Vel . at substrate	0.1-2.0m/s[39] -	Mean of 15.3 cm/s over redds[44]			
Stream flow fluctuations	Reduced[2] Flow variability accounts for suitable areas that are not used[14]		No evidence that sites selected on scour[16]	Chum spawn Night and day; water flows should be regulated the same[30]	
Dissolved oxygen levels	9mg/L[4] -			Lower lethal level for chum is 1.67 mg/l,	
Total dissolved gas (TDG)				Spawning areas and eggs affected if TDB within hyporheic	

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
				zone > 103%[31]	
Hydraulic conductivity	0.009 – 0.21 cm/s[12] 0.005 cm/s[2]				
Channel bed slope	0-5%[2] <4%[5]		Low-gradient tributaries[6]		
Upwelling		Upwelling in 60 % of redds river mainstem (BC)[44]			
Temperature (gravel)	Hypoheic temperature affect spawning habitat selection[22] -	Intragravel T of 4.5-6.0°C; mean of 6.8°C in water col; 6.5 °C at redd substrate[44]	2.2°C (Russia) to 10.7°C (California)[43] -	Lower fluctuation in hypoheic T. than for Chinook[22]	
TIME IN Egg pockets (in redds)	Eggs for 3 months; alevin for several weeks	-	4-6 Months[43] -		
TIME IN FRESHWATER	Spring run: Up to 1 year in freshwater after hatching[7,44] Summer run: Less than 1 year in freshwater after hatching[44] Fall Run: Less than 1 year in freshwater after hatching[44]	1-2 years[44] Full year in freshwater[9] Smolted at 1 year, matured in 1 additional year (BC), others took longer (Idaho)[18] Few weeks to 3 years[40] -	1 year[44] Most remain in freshwater 18 months from time eggs deposited in gravel[38] Remain in streams for a year or more, up to 15 months after emerging from nests[43]	Can be a short as 30 days after emergence from gravel (longer in colder water), Migration to ocean in February – May (Wash)[41]	Up to 7, most 2-3 years[7,44] Some adults that go to sea come back to freshwater for 6-10 months before spawn[23] -
ESTUARIES	Resided at		Resided at	Migrated	

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
	least from March to July as fry, fingerlings, parr[20] ; Subyearlings present all year, most common from May through September[25]		least from March to July as fry, fingerlings and yearlings[20] -	rapidly through[20] -	
TIME IN OCEAN	1-4, but precocious male parr 1 year or less[5] ; 2-3 years in the ocean, a few males mature in freshwater (and do not go to sea)[7]	1-4 years[40] -	Feed in ocean for about 18 months[38,] Remain in ocean for about 16 months[43] -	2-4 years[8] -	1-3 years, but some never leave freshwater[44] Most adults spend only 1-2 years at sea[7] -
Spring run	1-5 years[44]				
Summer run	1-8 years[9] Adults (spring, summer run) enter to spawn earlier with low river discharge and warmer waters[20]				
Fall run	1-8 years[9]			2-4 years[8]	
HABITAT					
General	Freshwater until adult, then sea	Freshwater until adult, then sea	Freshwater until adult, then ocean	Freshwater until adult, then ocean	
Eggs (in redds)	See above. Spawning started in Snake River			See above	

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
	as temperature dropped below 16°C, stopped at 5^0C[39]				
Alevin	Same as redds, still in gravel			Still in gravel in redds	
Fry	Mean water velocity of 45 cm/s or less; fish move to faster water as they grow[13] -			Emerge and may migrate immediately into estuaries, or feed in spawning areas[8]	
Parr (juvenile)	Yearling depths ranged from 1.5 m to 3.2 m, deeper during day[24]		18 months in freshwater[9] -	May remain in freshwater up to a year[8] -	Juveniles depth in water was 2.0 – 2.3 m; deeper at night[24]
Parr – (through dams)	A meta-analysis found positive relationship between outmigration water flow and survival[35]	Discharge flow affect time to pass through in British Columbia[19] -			A meta-analysis found positive relationship of outmigration water flow and survival[35]
Smolt		Enter smolt phase when 1 year, spend 1 year as smolt[18] Flow rate the primary factor	Smolt phase when about 18 months old[9] 96 hrLC50 for TDG = 120.5 %; 30day LC50		Some do not smolt, and thus do not enter ocean (=resident rainbow trout)[8] Flow rate

Parameter	*Chinook	Sockeye	*Coho	*Chum	*Steelhead
		explaining migration speed[34] 96 hrLC50 for TDG = 116.7 % 30day LC50 = 113.9%[37] -	= 116.2%[37] -		the primary factor in migration speed[34] 96 hrLC50 for TDG = 116. %; 30 day LC50 = 114%[34]
Adult (ocean)			Mature at about 3 year (after 18 months in ocean)[10] -	May mature between 3-5 yers[9] -	**Those that go to the ocean are steelhead salmon[8]** Mature at 2-3 years[8]
Adult (migration up river to spawn)	Fall run salmon slowed migration when water temperatures were > 20°C, moved into tributaries where water was 2-7° cooler[29]	Travel and arrival times correlated with temperature increases and flow decreases[33] Spawn in late summer and autumn[40]			Unlike other species in this table, after spawning some return to the sea, few make it back to freshwater to spawn again[38]
On recruitment	% land classified as urban, proportion of stream not meeting water quality standards, ability to recover from sediment flow events[11]				

NOTE: There is a Pink Salmon run on the Columbia River, but it is small and sporadic. In 2011, 979 were counted at Bonneville Dam, in 2010 there were 6. In only 6 years since 1938 were more than 100 counted in this location (htt;://www.gofishn.com/gofishn/14143columbia-river-in-washinton-seeing-record-pink-salmon-run/#ixzz2Kps4cPYd).

1. British Columbia (BC). 1997
2. Hanrahan et al. 2004, 2005
3. Hatten et al. 2009
4. Geist et al. 2000
5. Johnson et al. 2012
6. Division of Fish & Wildlife, Oregon (DFW). 2012.
7. Upper Columbia Salmon Recovery Board (UCSRC). 2007.
8. Dominguez, 1994
9. Columbia River Inter-Tribal Fish Commission (CRITFC). 2013.
10. Fulton, L.A. 1968.
11. Regetz, 2003
12. Arntzen, et al. 2001.
13. Tiffan et al. 2006.
14. Geist et al. 2008a
15. Beckman and Larsen, 2005.
16. Bigelow, 2003
17. Evenson, 2001
18. Kendall et al 2010
19. Pon et al 2009
20. Roegner et al., 2010
21. Keefer et al., 2008a
22. Geist et al., 2008b
23. Keefer et al., 2008b
24. Beeman and Maule, 2006
25. McCabe et al. 1986
26. Jepson et al. 2010
27. Cooke et al., 2008
28. Becker, 1972
29. Goniea et al. 2006.
30. Tiffan et al., 2005
31. Columbia River DART, 2013.
32. Arntzen et al. 2009.
33. Quinn et al., 1997
34. Giorgi et al. 1997
35. Cada et al. 1997.
36. Quinn and Adams, 1996
37. Nebeker and Brett 1976
38. Fulton, L.A. 1970.
39. Groves and Chandler, 1999.

40. Burgner, R.L. 1991.
41. Salo, 1991
42. Healey, 1991.
43. Sandercock, 1991
44. Lorenz and Eiler, 1989

APPENDIX B: Populations Levels of other Salmon that Spawn in the Columbia River

This report concentrated on Chinook Salmon, and used data from the other species of salmon for some comparisons. In this Appendix are figures illustrating yearly trends in numbers of other species of salmon counted at the three relevant dams (below and above the Hanford Site; and the first dam on the Snake River). There is some movement of salmon among areas. That is, a salmon may swim-up the Snake River and over the Ice Harbor Dam, and then go back to the Hanford Reach to spawn, or even move up the Yakima River to spawn (Liss et al. 2006).

The first figure shows population levels at Priest Rapids Dam for Sockeye and Chinook. Clearly, there are more Sockeye than Chinook. The yearly patterns are similar, with peaks in the same years, although the magnitude of the peaks differs. The following figure illustrates Steelhead and Coho, which are much less common than Sockeye, or even Chinook. The third figure illustrates Coho and Steelhead at McNary Dam, showing larger numbers. Thus, these two species either breed between the two dams, or go up the Snake River (or Yakima) to breed. For all four species there is a clear increase in the last decade.

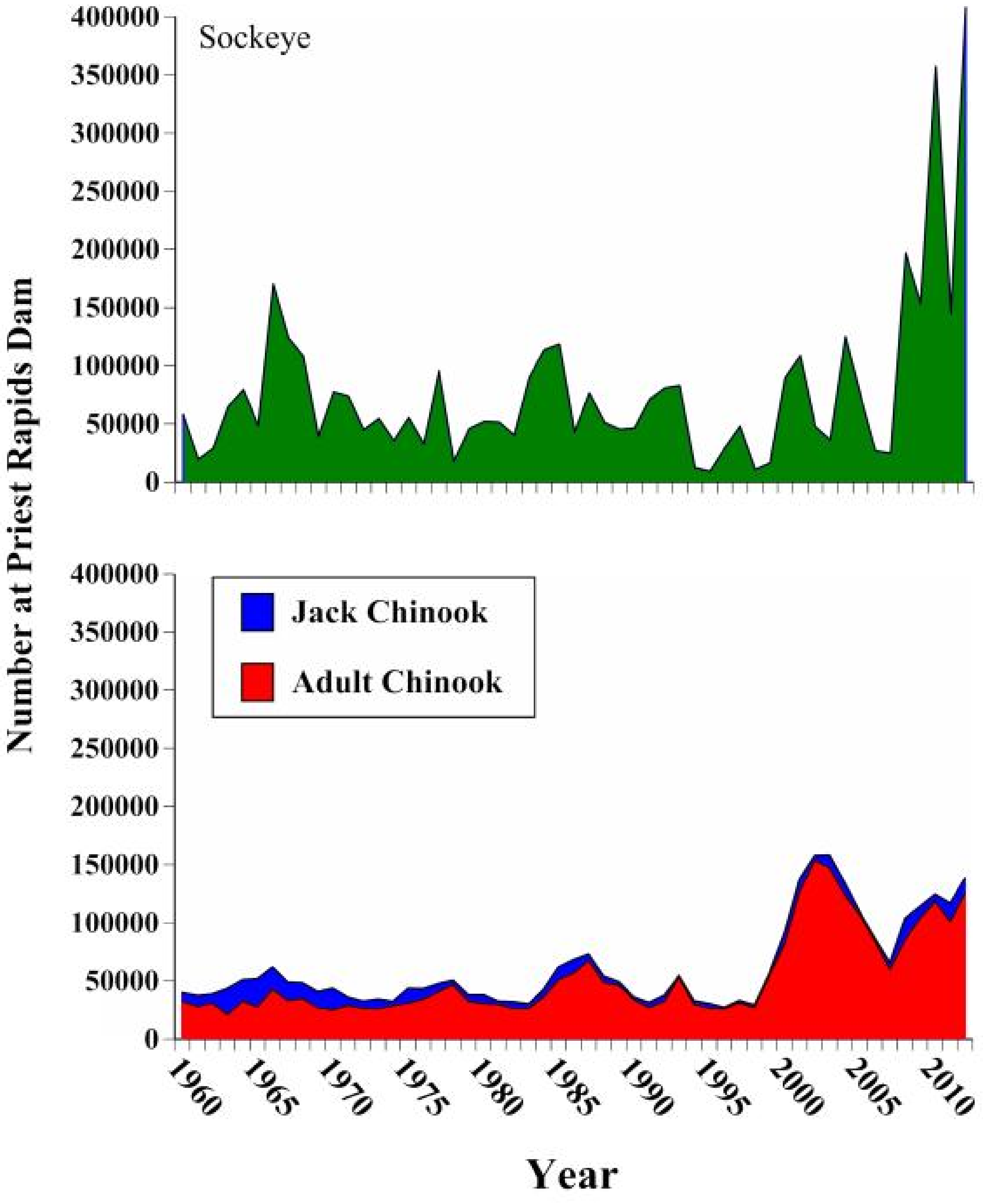

Fig. B.1. Numbers of Sockeye and Chinook Salmon Counted as they Passed through Priest Rapids Dam on the Columbia River (CBFAT, 2013).

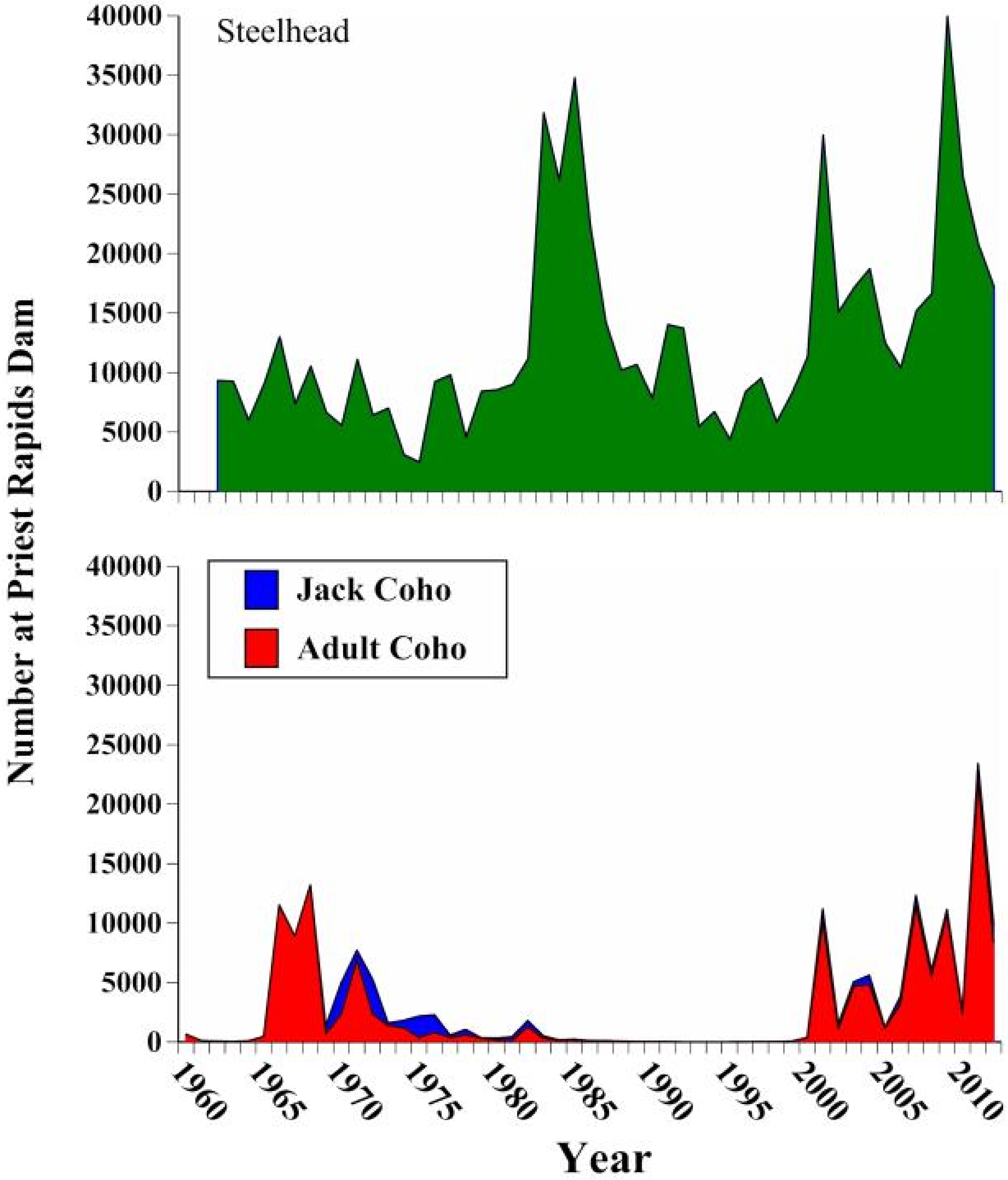

Fig. B.2. Numbers of Steelhead and Coho Salmon Counted as they Passed through Priest Rapids Dam on the Columbia River (CBFAT, 2013).

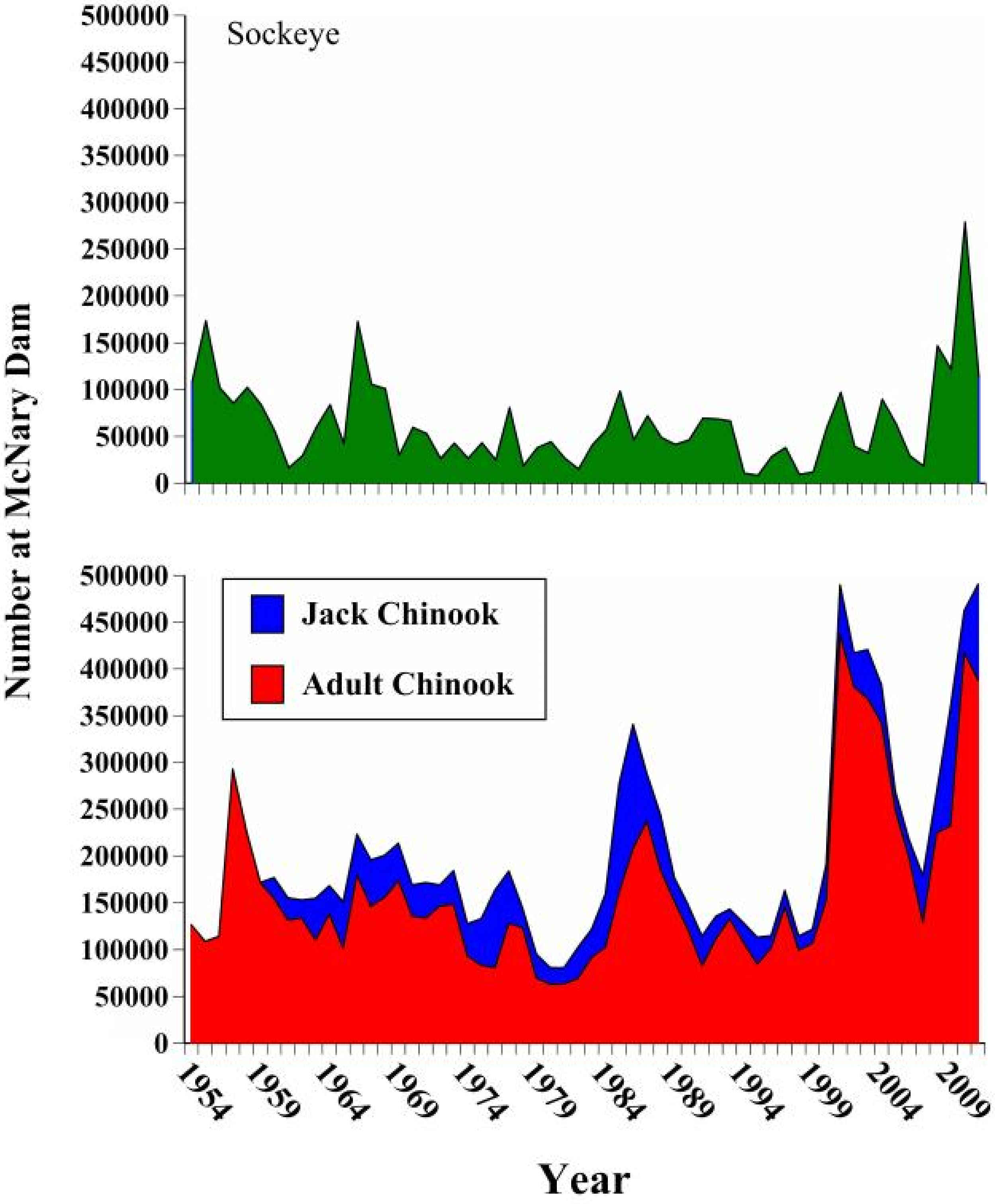

Fig. B.3. Numbers of Sockeye and Chinook Salmon as they Passed through McNary Dam on the Columbia River (CBFAT, 2013).

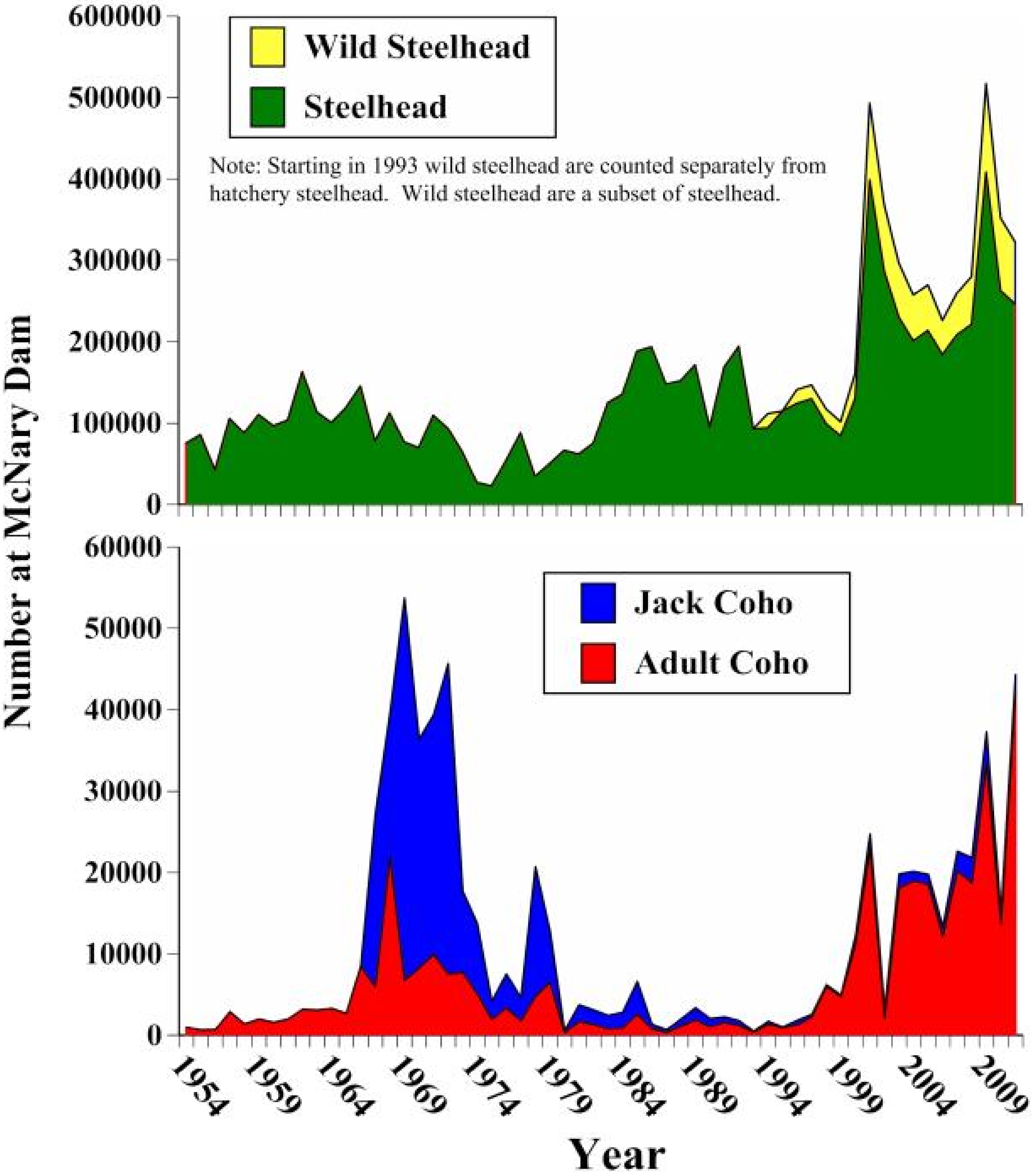

Fig. B.4. Numbers of Steelhead and Coho Salmon Counted as they Passed through McNary Dam on the Columbia River (CBFAT, 2013).

APPENDIX C. REPORTS ON MEASURES TO ENHANCE SALMON IN COLUMBIA RIVER. (© J Burger, CRESP)

Note: Except for Oregon Hanford Waste Board (2002), there is no mention of chromium.

Species	Stage	Methods	Reference
Chinook (spr/sum) Steelhead	Smolt	-Increased number of smolt hatchery releases -Install spillway deflectors to reduce dissolved gas saturation -Fingerling bypass at dams -Transportation of smolt around dams -Supplemental river flows to decrease smolt delays -Supplemental spill at dams to decrease turbine mortality	Raymond 1988
Chinook (fall)	Spawning	-Establish more normative flow regimes (e.g. sustained peak flows for scouring) -Consider population genetics and viability of seed populations.	Dauble et al. 2003
Chinook (fall)	Migration; Adult runs (for threatened Snake River)	-Main stream thermal characteristics (keep below 20^{O}C)and -Areas of refuge be considered when establishing regulations	Goniea et al. 2006.
Salmon	Salmon recovery	-Restoration of habitat for all life stages -Reduce mortality (including harvesting) -Planning hydropower mitigation in the context of normative river concept -Evaluation of mitigation measures to reach restoration goals	Williams et al. 1999
Salmon	Salmon recovery, particularly in estuaries	-Restoration of estuarine habitats (diked emergent and forested wetlands) -Flow manipulations to restore patterns -Hatcheries, harvest, and upriver habitat improvement. -Consider role of recovery strategies aimed at dominant runs (e.g. fall Chinook) on less abundant salmon -Recovery should expand diversity of salmon life history and habitat opportunities	Bottom et al. 2004
Salmon	Predation in estuary by birds	-Consider hatchery release patterns as the synchronous release provides abundant food for terns, cormorants, and encourages nesting -Timing of hatchery releases coincides with breeding season of the birds	Collis et al. 2001
Chinook salmon (fall)	Spawning in Hanford Reach	-Could increase spawning habitat by 100% by holding stream flows steady during peak spawning -Increase habitat by 21% to 1,133-2,265 m^3/s	Hatten et al. 209

Species	Stage	Methods	Reference
Salmon and steelhead	To the Columbia River system (mainly spring Chinook, steelhead and bull trout in Upper Columbia Basin	-Recovery actions for harvest, hatchery, hydro, and habitat. -Habitat recommendations include 1) protect areas with high ecological integrity, 2) restore connectivity in historical range, 3) establish or restore stream flows suitable for all stages, 4) Protect and restore water quality, 5) increase habitat diversity, 6)increase habitat diversity in short term by adding in-stream structure, 7) protect and restore riparian habitat along spawning and rearing streams, 8)protect/restore floodplain functions, and other habitat, 9) Restore natural sediment delivery, 10) Replace nutrients in tributaries, 11) Reduce abundance/distribution of non-native species, and 12) administrative actions dealing with collaborations, compliance, information provision, inventories, and permits. No mention of chromium.	UCSRB 2007
Salmon	Columbia River system	-Must address the entire natural and cultural ecosystem -Salmons require a network of complex, interconnected habitats. -Life history and genetic diversity are crucial	Liss et al. 2006
Salmon	Columbia River system (federal and state approaches)	-Mainstream habitat -Tributary habitat -Hatchery reform -Harvest -Monitoring -Climate change -Institutions -Need to fill data gaps (what is mean by some of the recommendations, what can be done about climate, information on habitat, relationship of harvest to recovery goals, integration)	Bisson et al. 2006
Salmon	In the Hanford Reach	-**DOE** should demonstrate existing containment systems meeting required performance standards. -**DOE** should demonstrate that chemical barrier is effective -**DOE** should fund additional studies to determine if chromium VI is harming salmon and other fish -**EPA and states** should study whether Chromium VI standard (20 mg/L) is ecologically protective.	OHWB 2002

Species	Stage	Methods	Reference
Columbia River Basin[1]	State of Columbia River Basin Toxics	-Report deals with mercury, DDT, PCBs, PBDEs. -Report indicators are juvenile salmon, resident fish, sturgeon, predatory birds (Osprey, bald eagle), aquatic mammals, and Asian clams. -"These species can help us understand trends in the levels of toxics in the Basin and judge the effectiveness of toxics reduction efforts"(from Executive Summary). **No mention of Chromium**	EPA 2009

1. Steering Committee included people from EPA, USFWS, IDEQ, USGS, WADOE, WADOH, NPCC, ODEQ, The Confederated Tribes and Bands of the Yakama Nation.

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