Using Salmon as a Bioindicator of the Health of the Columbia River at Hanford – 15534

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ABSTRACT

Assessing human, ecological, and cultural health and well-being on- and off-site is an important aspect of managing legacy wastes and environmental remediation on U.S. Department of Energy sites. Such an assessment is especially important at places such as Hanford because the Columbia River runs through the site. The Columbia River is central to the culture and economy of the northwest, especially to the Tribes. While a full range of other bioindicators are used to determine the health of the river with respect to contaminants, salmon are the iconic, keystone species in the Columbia River of concern to the full range of regulators, managers, Tribes, and the public. A biomonitoring plan that will assure the public and others that the activities of DOE are not adversely impacting the salmon populations in the Columbia River is critical for long term stewardship, both of the Hanford Site and the River and its resources

Numerous factors affect salmon populations, including different life stages, habitat variables, and anthropogenic effects, including hexavalent chromium. Based on a literature review of the factors affecting populations, a conceptual model was developed for effects on salmon population stability. Salmon have a life history that includes laying eggs in gravel (redds) at the river bottom and then spending several life stages in fresh water and maturing in saltwater before they return to their natal streams or rivers to breed. All of these phases are potentially vulnerable to a range of natural and anthropogenic factors. Eggs in redds in the river bottom are vulnerable to water erosion, dewatering, oxygen levels, predators, and contaminants, while juveniles (fry, parr, smolts) are vulnerable to water currents, oxygen levels, predators, contaminants, and negotiating dams. When adults return to the river up to 7 years later, they face these same factors, as well as intense fishing pressures. The major factor affecting salmon populations may well be the fight to swim upstream, around dams, to reach traditional spawning grounds.

While the data provided in this study relate to salmon at Hanford, the overall conceptual framework provides a paradigm for evaluating other sensitive indicators at other Department of Energy sites. The framework provides a method to insure the Tribes and public that the health and well-being of an important economic, cultural, and aesthetic species is being adequately addressed, and suggests the types of data needed to address the issue.

INTRODUCTION

Salmon are an important resource in the Pacific Northwest, including the Hanford Reach where the Columbia River flows along the Department of Energy's (DOE) Hanford Site. Salmon are important bioindicators because of their Tribal, cultural and economic importance to the Pacific Northwest [1-3]. 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 [4,5]. For most salmon species adults spawn only once, and then die. There are several species of salmon, and many genetically distinct "stocks" of salmon in the Pacific Northwest, resulting in controversy about the taxonomy. Salmon are heavily fished both recreationally and commercially, as well as being culturally important to Native Americans [6].

In the Columbia River, there are five species of salmon [7], and although this document focuses on Fall Chinook Salmon (*Oncorhynchus tshawytscha*) (King Salmon), the others are important. Adult Chinook include an endangered spring run, a summer run, and the large, non-endangered fall run which spawns in the autumn[8,9]. The Hanford Reach (section of the Columbia River adjacent to the DOE's Hanford Site), is one of two significant spawning habitat for fall Chinook Salmon [10]. Historically, fall Chinook Salmon spawned over a 900-km distance of the Columbia River, but their spawning grounds are now restricted because of dams and development [11,12].

Salmon conservation in the Pacific Northwest is complicated by the hydroelectric system of dams [12,13], harvest limits [14], genetic diversity, and the large-scale supplementation of populations with hatchery fish [15]. Harvests of Chinook Salmon from the Columbia River system have been as high as 19.5 million Kg in 1889, but by 1960 it had declined to less than 5 million Kg [16]. 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. After the Boldt decision regarding the fishing rights of Native Americans, salmon populations began to increase, partly as a result of a more holistic approach to management (R. Jim, pers. comm.). An additional issue is the contribution of hatchery-raised fish producing more offspring that reach adulthood than wild salmon in the same rivers [17]. Hatchery fish seldom have as high adult survival rates as indigenous fish [18]. This may change as Tribal fish hatcheries mimic more natural conditions by providing higher flow, elevation gradients, and exposure to predators (Nez Perce hatcheries, G. Bohne, pers. comm.). Unlike many bioindicators, there are many hundreds of papers on salmon biology, fisheries, and conservation in the Columbia River Basin. Maintaining healthy salmon populations is a local, regional, and national goal [1].

Because the DOE's Hanford Site borders the Columbia River, there is concern that radionuclides and other contaminants in soil or ground water may be entering the river are impacting salmon and the ecosystem generally. The Hanford Site was developed during World War II to produce plutonium for the atomic bomb, and it played a major role in the US nuclear program, including operation of nine plutonium production 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 in various ways, eventually contaminating groundwater. Subsequent discharges were less direct, but contributed to major sources with ongoing release to groundwater at several of Hanford's reactor sites. Hexavalent chromium in plumes is moving slowly toward the river, and entering the river through underground pathways and emerging as springs, seeps, and upwellings, but is quickly diluted by the river. Extensive soil excavation and pump and treat have been carried out to remove sources and mitigate chromium contamination. Recent fish advisories for the middle Columbia River are based on PCBs and mercury [19]. Fish are often used as bioindicators [20, 21].

The overall objective is to provide a paradigm for examining the factors that affect salmon populations, including different life stages, habitat variables, and anthropogenic effects, including hexavalent chromium. What is needed to develop salmon as a bioindicator of the health of the river near the Hanford Site is information on 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 chronic and acute effects of chemicals and radionuclides (e.g. exposure to chromium, chromium levels in fish in the Columbia River, potential consequences), and management implications of the aforementioned factors. The objective of the study was not to provide all of this information, but rather to develop a paradigm for assessment.

METHODS

Our methods consisted of reading and synthesizing information from books on salmon and the Columbia River, refereed literature, and grey literature where it was available to the public. As a policy, the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) prefers to use information that is available to the public to ensure transparency and allows free discussion.

A PARADIGM FOR SALMON AS A BIOINDICATOR

Background on the Columbia River Basin and Salmon

The Columbia River Basin once had the largest salmon runs in the world (10-16 million fish), but these have decreased to about a million upriver salmon [22]. The Hanford Reach, along the Department of Energy's Hanford Site, is the largest mainstream stronghold for fall Chinook, and it once supported 90% of the fall Chinook that return to the central Columbia River [4,23] although in recent years this percentage has dropped because of increases in spawning in the Snake River [24]. Different segments of the Chinook population run up river in spring, summer, and fall. The much smaller spring and summer runs are considered endangered [25], and do not breed in the main Columbia River, but in small tributaries. 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 [2,6,26]. Even when salmon populations were low, salmon was a major food item for native peoples, and migratory salmon had well-established spawning populations in the Columbia Basin [26].

Habitat quality has been affected by the dams that alter water levels and current characteristics. Thus, the biggest habitat difficulty for salmon populations is the inability of salmon to reach most of their traditional spawning grounds, and variations in water level caused by water control.

Flows through the Hanford Reach are partly controlled by the 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 it partly controls flow in the Hanford Reach [27]. Understanding the levels of assessment for salmon, as well as the measurement endpoints (what can be measured), is critical to habitat protection. In this document Chinook Salmon are used as a bioindicator, although information on other species is presented where informative. Chinook Salmon are the most abundant species of salmon in the Columbia River Basin [17].

Life History and Habitat Requirements

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) [28]. Some Chinook salmon spend their entire lives in freshwater [28, 29]. Adults come back to their natal river to spawn (and die there). When adult salmon arrive upstream, they dig or excavate nests (located in spawning areas called redds) in the gravelly sediment. 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 [30]. Those that hatch in the river itself (summer and fall runs) typically spend less than a year in freshwater before migrating to the sea [25], Dauble and Geist [31] 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 [28]. Life cycles are shown in Fig. 1.

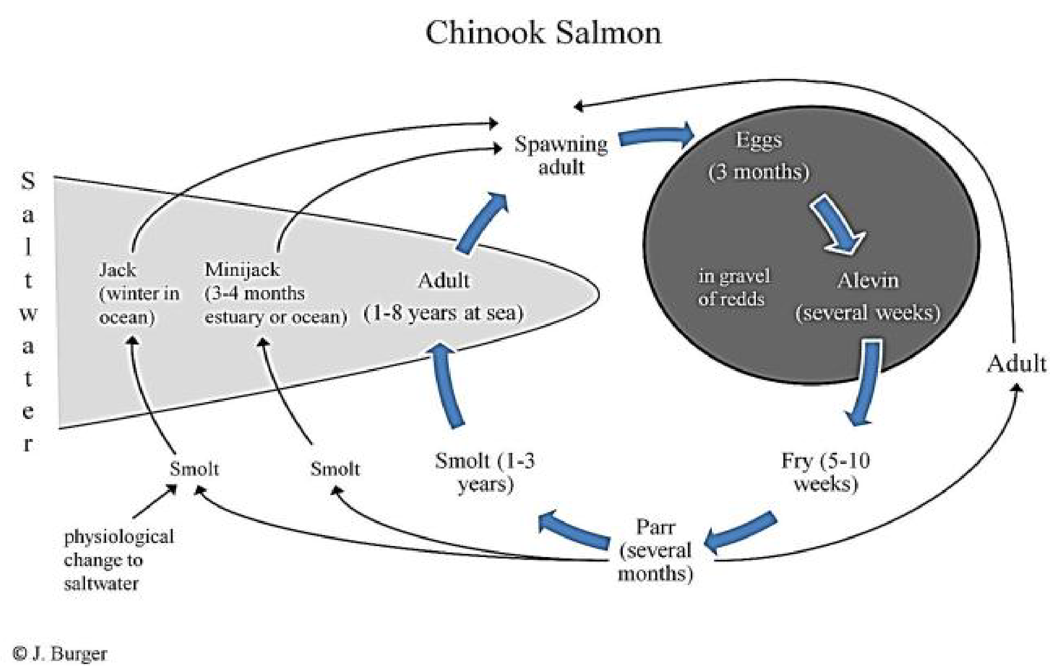

Fig. 1. Generalized Life History of the Chinook Salmon in the Columbia River and Pacific Northwest [4, 28,29].

Life history strategies differ in Chinook Salmon (Fig. 1). Males, for example have several strategies that results in a continuum of the different strategies [28]. Males may mature a year earlier than the females from the same cohort (i.e. precocious maturation). Further, there are different life history strategies that occur in the Columbia River – fish that migrate to the ocean in their first year of life (called jacks) and fish that spend a full year in freshwater before going to the ocean [32]. Jacks winter in the ocean and return relatively quickly to breed in natal streams. Determining vulnerability of each life stage is a matter not only of the timing and duration of a given stage for an individual but also determining the length of each stage. That is, 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).

Vulnerabilities that Suggest Measurement Indicators for Salmon

From the life history (Fig. 1), it is clear that salmon have different vulnerabilities at different points in their life cycle, and these vulnerabilities can lead to measurement endpoints. The critical life stages are: 1) Spawning and fertilization, 2) Eggs and alevin in the gravel are place-based, and dependent upon the conditions at the nest site (called redds), 3) Free-swimming fry and parr that must feed, grow, avoid predation, and successfully move downriver, 4) Smolt with maturing osmoregulation function, move downriver to the estuaries, 5) Adults that live in the sea, remaining for several years before returning to natal streams and rivers to spawn, and 6) Adults returning upriver and upstream to spawning areas.

Spawning and Fertilization: Females "dig" redds in gravel and deposit eggs, male deposit milt and fertilization occurs within seconds. Eggs imbibe water and harden in hours.

Eggs and Alevins: Environmental conditions might play a key role in survival of eggs and alevins (recently hatched young that remain in the gravel) if contaminants have the potential to affect eggs and alevins, and if contaminants are present in sufficient concentrations. Exposure to contaminants during this stage is due to exposure to pore water. There is concern about the potential impacts of chromium (hexavalent) on eggs and young [10,33] although some studies have failed to find an effect on fertilization [34].

Fry/Parr: Once the young hatch, and swim up to the gravel/water interface and begin to eat, they are vulnerable to contaminants in the sediment-river interface and food chain.

Smolt: As fry grow into smolt, they move down-river to the estuary where they are vulnerable to predators; up to 17 % of smolt are captured by terns nesting in dense colonies at the mouth of the Columbia River [35,36].

Adults: Adult salmon go to sea and spend up to seven years foraging in the ocean and avoiding becoming prey. California and Steller Sea Lions prey on adult salmon [37], and predatory fish prey on them as well.

Spawning Adults: Adults returning to the Columbia River to spawn face two main stressors: making their way upstream to spawning areas and selecting sites for redds and spawning successfully. Changes in climate may affect different Chinook populations differently [38].

Redds are in contact with pore water and are located to allow suitable water flow to provide sufficient oxygen. On the other hand, redds cannot be in water with a high velocity that would dislodge eggs. Selection of suitable nest pockets within spawning areas (redds) is critical to reproductive success, and spawning habitat is limited by deep water and low water velocity [39,40]. Important substrate characteristics are pebble size, grain size in the nesting area, water depth, and water velocity. The spawning areas need downward flow of water through the part of the nest where the eggs are located (i.e., eggs are about 22 cm below the surface). Water must flow at least to these depths to provide oxygen [41]. Fall spawning criteria developed by Hanrahan et al. [39] included water depth (0.30-9.5 meters), velocity (0.23-2.25 meters/second), substrate (25-305 mm grain size), and channel bed slope (0-5 % slope). The salmon prefer nesting in areas with water velocities greater than 1 m/s, and where streamflow fluctuations are low [42]. Excessive fine sediment impairs egg survival (Honea et al. 2009). Geist et al. [44] 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 was about 9 mg/ L [45]. Characteristics are summarized in figure 2 and Table I.

Table I: Key Characteristics for Redds and Spawning of Chinook Salmon in the Columbia River.

Characteristic	Optimal values	References
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. 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
Conductivity	0.009 to 0.21 cm/sec	Arntzen et al. 2001

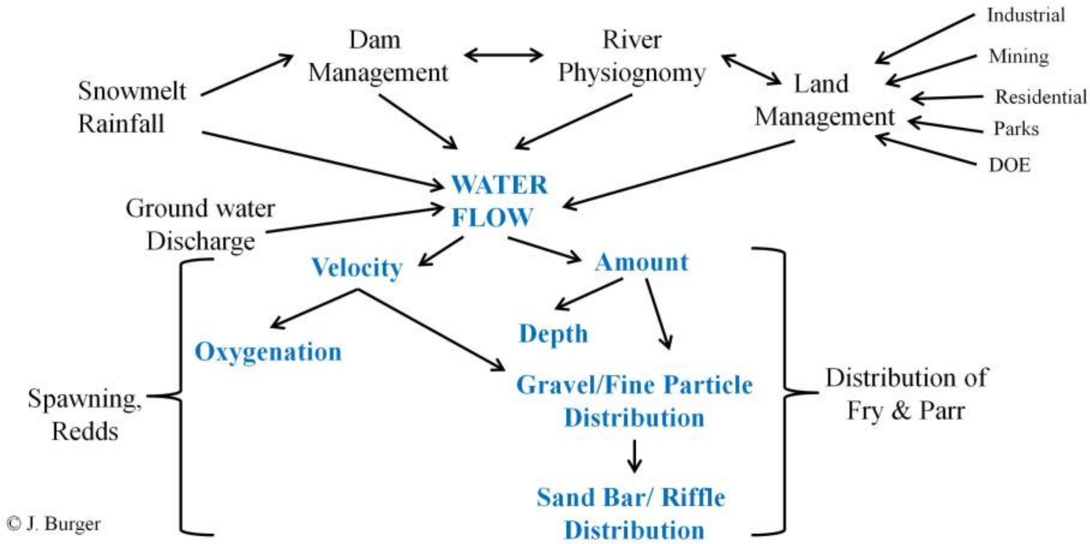

Fig. 2. Some of the factors affecting salmon spawning and hatching success.

Hexavalent chromium is a contaminant of potential concern for salmon in the river. No effects on salmon were found in Hanford-relevant hexavalent chromium exposures up to 266 micrograms/L for fertilization or hatching [33,34], or survival of alevins (that do not eat, but remain in the gravel [49]. There are likely no effects of hexavalent chromium on populations of salmon fry, however, because: 1) after swim-up the fry are no longer in gravel (thus, no longer exposed to pore water), 2) fry feed on invertebrates (mainly insect larvae), and therefore are exposed to hexavalent chromium at river concentrations rather than upwelling concentrations, and 3) hexavalent chromium concentrations in Columbia River water are below detection or practical quantification levels.

Measurement Endpoints for Salmon as a Bioindicator

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) [50]. The Tribes affected by the Hanford Site are co-managers with state agencies of Columbia River fisheries [51]. Trends in salmon numbers, and spawning activity (sustainability), are of concern to the Tribes.

Another way to examine salmon life history and habitat cycles is to look at the potential temporal overlap in the different stages, and to examine variability in life history phases by month (Fig. 3). From Fig. 3, it is clear that the variability in individual salmon spawning results in relatively long periods when salmon can be vulnerable. Fall Chinook Salmon, the major run in the Hanford Reach, begins in late summer, and spawning typically begins in mid-October and through November [52].

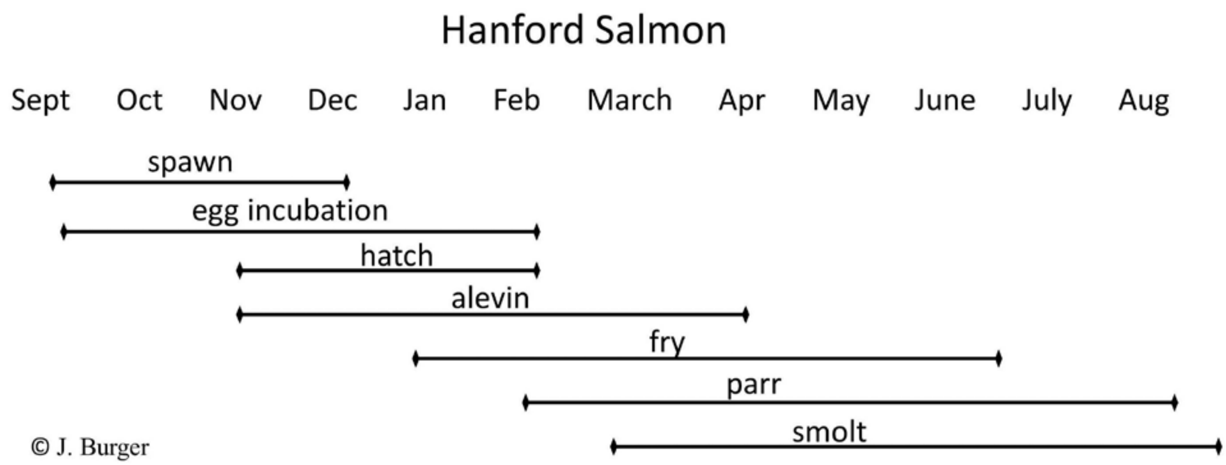

Fig. 3. Temporal Overlap in Life Cycle Stages in Fall Chinook Salmon in the Columbia River, derived from several sources.

Table II: Summary of Measures to Increase Salmon Populations (particularly Chinook in the Columbia River). 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 flow	Raymond 1988
Chinook (fall)	Establish normative flow regimes	Dauble et al. 2003
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
Salmon in estuaries	Restore estuarine habitat; Plan hydropower mitigation Restore flow; Time releases to reduce bird predation	Bottom et al. 2004;Collis et al.

		2001
Chinook in Hanford Reach	Hold stream flows steady during peak spawning Recovery actions aimed at harvest, hatcher, 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	DOE, Environmental protection Agency (EPA) and others should fill data gaps with respect to effects of chromium on salmon to determine how to increase survival and population levels.	OHWB 2002 Bisson et al 2006

The factors affecting populations (Table I) and possible recovery measures (Table II) were used to develop a conceptual model of the factors that affect salmon populations (Fig. 4). This figure indicates those factors affecting salmon directly, but other external factors affect water flow and the river physiognomy on a landscape scale (refer back to Fig. 2), which affect riverine habitat suitability. While contaminants do not figure prominently in any discussions of these factors, they are nonetheless included in the model.

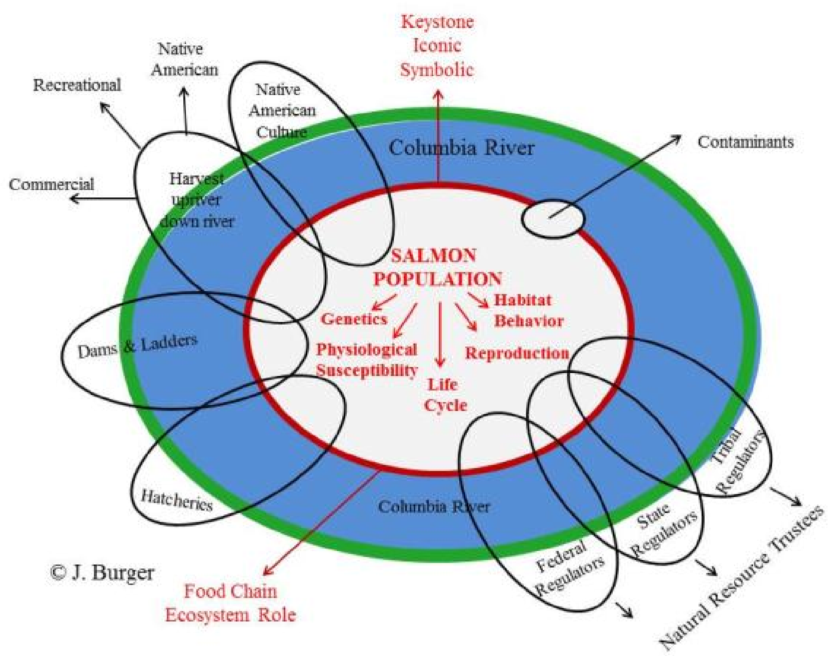

Fig.4. Factors affecting Chinook Salmon populations in the Columbia River. Salmon are affected by internal (shown in red) and external factors (egg-shaped factors operating terrestrially and in the Columbia River). Information developed from many references.

In one book about *Pacific Salmon Life Histories*, toxics, chemicals, radioactivity, and chromium are not even mentioned in the index [58], nor is Hanford mentioned except to note that the strongest populations of fall Chinook occur along the Hanford Reach [1]. The book, *Return to the River: Restoring Salmon to the Columbia River* [4] also does not mention chromium, although it does mention aluminum, sewage, pulp mills, and metals from mining. This book notes that "water pollutants, other than from fine sediments, increased temperature, and metals from mining districts, generally are not considered a major factor in salmonid declines nor particularly problematic for recovery. However, the available data may not 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" (page 211) [4]. A suite of measurement endpoints can be used for salmon as bioindicator of the health of the Columbia River (Table III).

Table III. Measurement Endpoints available for Salmon as a Bioindicator of Health of the Columbia River. These endpoints are not presented in order of significance since this value judgment should be made by resource managers, regulators, stakeholders, and Tribes (after Burger et al. 2013, Unpubl data). .

Physical	Snowmelt levels Presence of suitable gravel beds/river location Grain size of gravel Water depth and velocity Stream flow fluctuations Dissolved oxygen levels Chanel bed slope Hydraulic conductivity
Biology of Salmon	Population levels of salmon – for each species Different life stages, over years, dams Growth and survival by life stage Time to reach spawning Location and number of redds/location/river section Toxic chemical levels by life stage Change in suitable spawning areas over time
Other Biotic Factors	Predation rates (particularly of smolt in estuaries) Food availability
Contamination	Contaminant levels in different life stages (health of salmon and their predators) Contaminant levels in adults (human health, particularly for Tribes) Determining contaminants of concern (human and eco-receptor health)
Recovery Measures	Hatchery Production Contribution of hatcheries to spawning adult population Dam passage success (including fallback rates)

	Harvest measures Stream flow data measures
Tribal Measures	Harvest rates (and relationship to traditional harvest) Hatchery production Success of tribal/non-tribal hatcheries in contribution to spawning adults

DISCUSSION

This evaluation provides an overview of salmon biology, the factors affecting salmon success and populations, a model for the factors affecting salmon success, and recovery measures proposed by a range of authors and agencies. These information sources were used to develop a suite of possible measurement endpoints that would be useful for assessing the health of the Columbia River, using salmon as a bioindicator. It should be remembered that several books [4, 18, 58] and hundreds of papers have been written about salmon. It was not the intention of this study to describe fully the biology of neither salmon nor all the factors affecting reproduction, success, and population levels of salmon. Rather, information is summarized that is useful in developing measurement endpoints that in concert contribute to the use of salmon as a bioindicator of the health of the Columbia River.

The importance of salmon to the Native American culture, and to the culture of Northwesterners in general has contributed to knowledge of salmon. The fact that there is so much known about salmon in general and Fall Chinook Salmon in particular, allowed us to develop a varied and rich set of measurement endpoints, far more perhaps than are available for other biota.

For the Hanford Site and DOE, a listing of possible measurement endpoints provides a basis for developing a biomonitoring plan that has salmon as its centerpiece. Such a plan should also include some other species that represent different trophic levels, including benthic predators.

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