Canada's Fraser River

Reasons for sockeye salmon declines with a comparison to Bristol Bay

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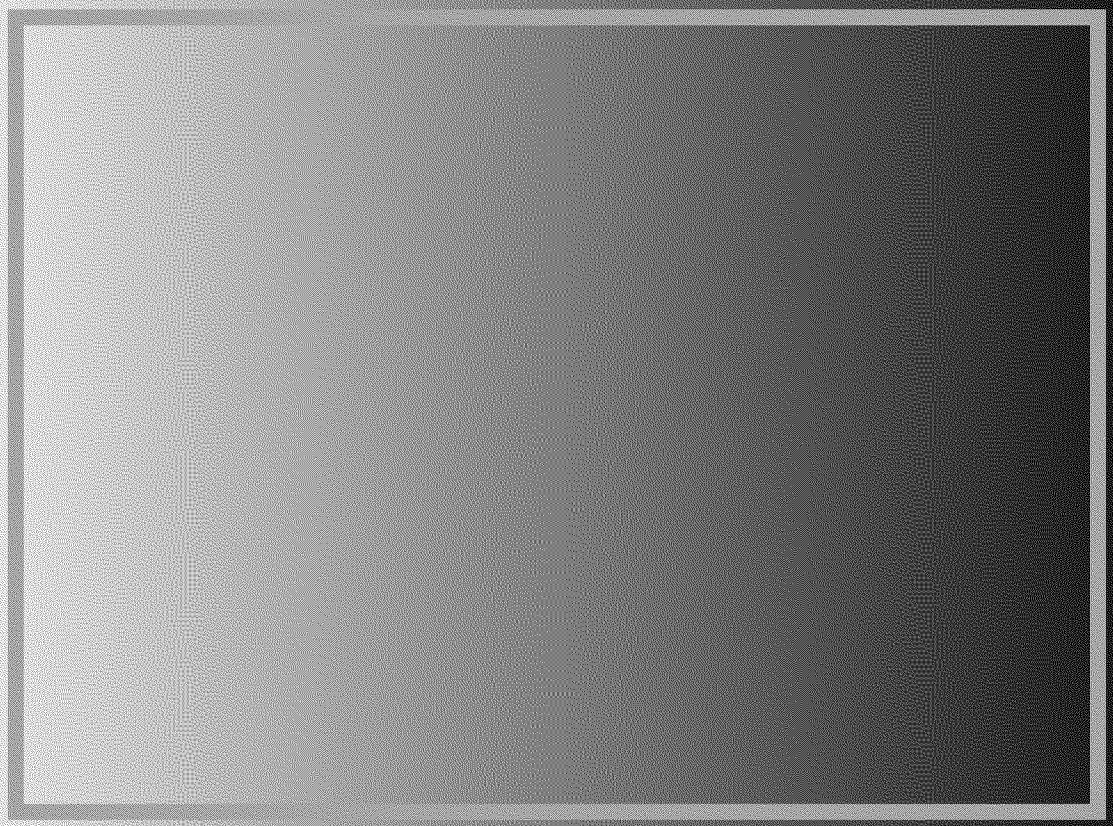

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Canada's Fraser River: Reasons for sockeye salmon declines with a comparison to Bristol Bay

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Introduction

Recently, Fraser River sockeye populations have been compared to those of Bristol Bay by proponents of mining projects in Bristol Bay, who cite Fraser River sockeye as an example of the 'co-existence' between mining and fisheries (Joling 2011). Due to distinct physical and biological nature, as well as vastly different levels of urbanization and industrialization, the two systems make an unlikely pairing. However, current state of the Fraser River system with impaired water quality, human development, changes in prey base and prey bases, and climate change has resulted in the lowest productivity of the Fraser River sockeye in fifty years.

Fraser River sockeye salmon populations are suffering from myriad problems associated with urban and industrial development, leading to dramatic decreases in productivity, multiple fisheries closures, and federal and international population listings. In freshwater, there are stressors from contamination (from mining, wood product and other industrial facilities), introduced predators, and increased river temperatures. In the marine and marine environment, stressors are related to household and industrial waste, shipping, loss of habitat, and warmer marine water temperatures.

While the blame for the declines simply cannot be pointed in a single direction, the current state of Fraser sockeye is unfortunately the disastrous example of the co-existence of human development and salmon.

Status of the Fraser River salmon

The Fraser River is known as the greatest salmon river in the world and indeed is the Canada's largest salmon producer (Burgner 1991). Sockeye salmon (*Oncorhynchus nerka*)

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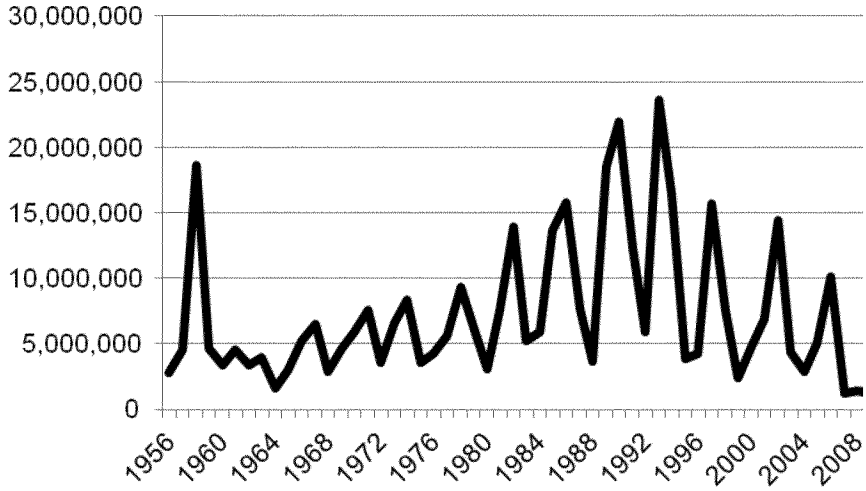
are the most commercially valuable species in the Fraser, and generated hundreds of millions of dollars annually until the mid-1990s (DFO 2011). In recent decades, however, total runs, productivity (recruit per spawner), and commercial value suffered wide fluctuations, and ultimately significant declines (Pacific Salmon Commission data, 2011). Productivity currently is at its lowest, indicating populations are barely replacing themselves (Figure 1, Peterman 2010). Low returns resulted in fisheries closures in the last 6 of 10 years, including three consecutive years from 2007 to 2009, when total runs failed to exceed 10 million fish (Figure 1, Pacific Salmon Commission data).



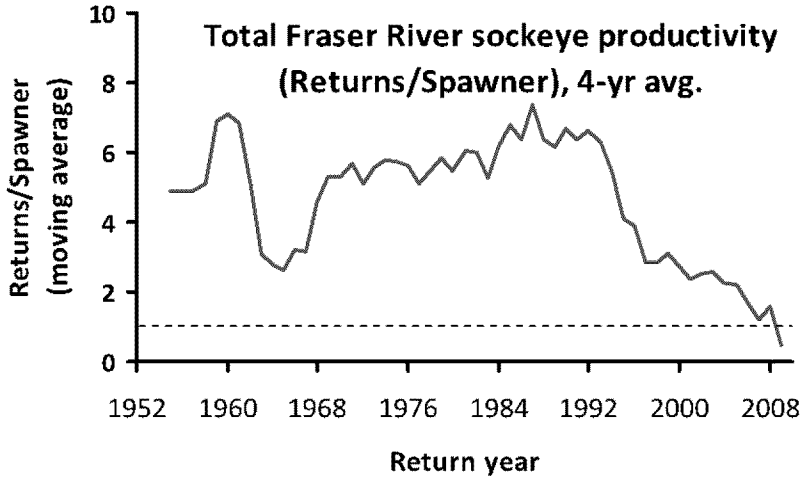


Figure 1. Total Fraser River sockeye returns (top) = harvest + escapement for each year. Moving average of adult returns per spawner across all Fraser River sockeye stocks (not including the minor jacks component) divided by total spawners 4 years before. The horizontal dashed line indicates the productivity at which population can replace itself, i.e., returns/spawner = 1. Pacific Salmon Commission data in Peterman 2010.

During the most recent conservation status review, the International Union for the Conservation of Nature (IUCN) categorized 51 of Fraser sockeye salmon stocks as threatened: none Critically Endangered, three as Endangered, and as Vulnerable

(Rand 2008). Lake sockeye salmon in the Fraser are designated endangered by the Canadian government Committee on the Status of Endangered Wildlife in Canada (COSWEIC; DFO 2011).

Prodigious research into causes of declines includes an ongoing $20 million dollar federal judicial inquiry. To date, results suggest salmon and their essential habitats suffer from a multitude of stressors. The following discussion summarizes some of the peer reviewed and gray literature on Fraser River sockeye declines, and concludes with a brief comparison of Fraser River with the world's largest sockeye salmon producing system, the Bristol Bay watershed in southwest Alaska. This discussion will be updated as results emerge from the Cohen Commission federal inquiry, currently underway.

Fraser River freshwater environment

Contaminants

MacDonald et al. (2011) systematically evaluated over 200 aquatic contaminants in the Fraser River basin in addition to potential exposure and harm to sockeye. The study indicates contaminated surface water, sediment, as well as accumulation of contaminants in tissue, could pose hazards to spawning, rearing, and migrating salmon. Primary elements of concern were pH, total suspended solids (TSS), turbidity, nutrients (nitrate, nitrite, and phosphorus), major ions (chloride, fluoride, and sulphate), metals (aluminum, arsenic, boron, cadmium, chromium, cobalt, copper, iron, lead, mercury, nickel, selenium, and silver), and phenols. Concentrations of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin equivalents occurred at sublethal concentrations that may adversely affect reproduction. Data insufficient to thoroughly examine impacts of endocrine disrupting chemicals such as pharmaceuticals, personal care products, industrial chemicals, pesticides, inorganic and organometallic compounds, and biogenic compounds (MPCA 2008), though authors concluded they undoubtedly were entering the Fraser River and likely have impacts on sockeye development and reproduction. For example, the occurrence of feminized male sockeye salmon (MacDonald et al. 2011) is a likely result of exposure to endocrine disrupters.

Sources of contamination are numerous. Twenty eight major mines (Figure 2), many small placer mines, 10 pulp and paper mills, 99 sawmills, plywood mills, and other wood product facilities, 15 wood preservation facilities, 17 cement and concrete facilities, 38 seafood processing facilities, 37 municipal wastewater treatment plants, 37 salmon enhancement facilities (Appendix 1), 83 municipal industrial landfills, several manufacturing facilities, as well as the oil and gas industry operate within the watershed (MacDonald et al. 2011). Many of the above mentioned facilities are permitted to discharge contaminants of concern (MacDonald et al. 2011) and accidents occur. For instance, 51 spills were reported from various facilities during a four month period in 2007 (MacDonald et al. 2011). Of the 2866 sites listed in the Canadian Contaminated Sites Registry nearly 15 years ago, 2699 (94%) were located in the Fraser River watershed (MacDonald et al. 2011). The number of contaminated sites is currently estimated to exceed 5,000 (MacDonald et al. 2011).

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Human activities also contribute non-point source pollution to the Fraser River. Forest management activities, agricultural operations, and stormwater runoff can contain sediment, fertilizers, insecticides, fire retardants, and other contaminants (MacDonald et al. 2011, Nelitz et al. 2011). MacDonald et al. (2011) indicate substantial quantities of suspended solids, nutrients, metals, phenols, and total hydrocarbons have been released to the Fraser River from non-point sources. Finally, atmospheric sources of pollutants such as persistent organic pollutants and mercury, which can also impact aquatic ecosystems (Muir et al. 2005), include forest fires, volcanoes, and carbon emissions (MacDonald et al. 2011).

Land Use

Nelitz et al. (2011) additionally examined impacts of mining, forestry, agriculture, hydroelectricity, urbanization, and water use in the freshwater environment and their potential impacts on the Fraser sockeye salmon populations.

Mining

Several types of mining take place in the Fraser Basin (Figure 2): placer gravel mining, industrial mineral production, metal mining, oil and gas production, and coal mining. Ashton operating mine, Gibraltar, produces acid mine drainage associated with high levels of dissolved copper and other metals, exceeding federal and provincial effluent discharge criteria by several orders of magnitude (Errington and Ferguson 1987). Placer gold is the dominant mining activity in the basin and may have the most significant impacts to salmon due to sediment effects (Nelitz et al. 2011).

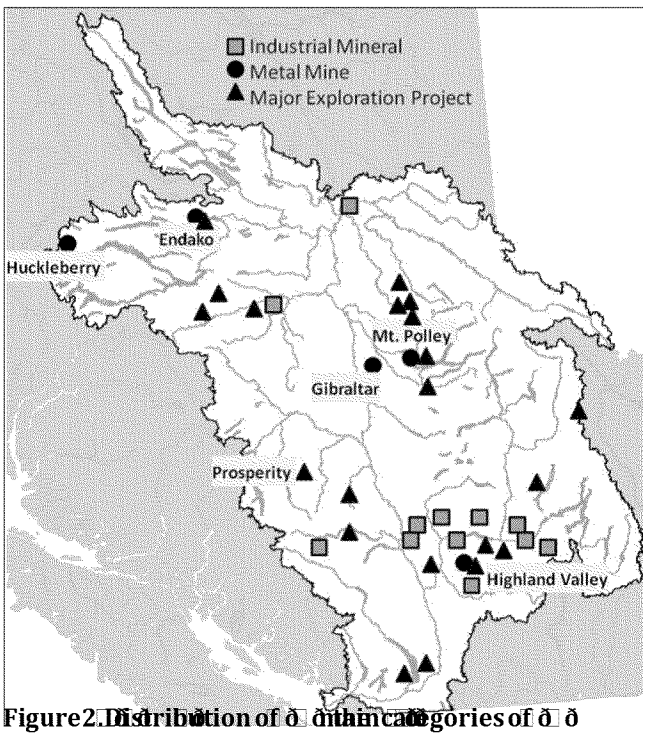

Figure 2. Distribution of the main categories of large mines in the Fraser River Basin. (Nelitz et al. 2011)

Hydroelectric

Two large hydroelectric projects within the basin, BC Hydro's Seton River power project and Alcan's Kemano Project on the Nechako River that affect water temperature and flow, at the time inhibiting migration ability of the sockeye salmon (Nelitz et al. 2011). Small scale hydropower projects, which can affect Total Gas Pressure (usually nitrogen supersaturation), gravel supply, and water temperature, also exist in the basin, though in a fairly numbers (about 20, Nelitz et al. 2011).

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Urbanization

Water demand was associated with high human densities, largely in lower portions of the Fraser River basin. Population growth, associated with urbanization, was 81% in the lower Fraser and 125% in municipalities upstream of the British Columbia in the past 20 years. Urbanization caused alterations to salmon habitat from impervious surfaces including roads, changes in hydrology, stream crossings and channelization.

Forestry

While forest harvest has decreased significantly in the recent decades, there is the more than stream crossing per square kilometer in the spawning areas and migration corridors (MOE 2008). Crossings often serve as barriers to movement (Warren and Pardew 1998), and the impact of the history of anadromous salmonids (Groot and Margolis. Further, up to 90% of the area in the some watersheds was disturbed by the Mountain Pine Beetle infestation, potentially increasing fire risk and sedimentation as well as impacting stream hydrology (Nelitz et al. 2011).

Agriculture

The land area occupied by the agriculture has increased in the past twenty years. Agriculture can cause physical alteration to the stream, riparian zones, and floodplains; increase sedimentation and destabilize stream banks causing widening of the stream channels; remove vegetation which can increase stream temperatures; compact soils subsequently increasing runoff; deway groundwater sources important to the maintenance of streamflows and temperature regimes; increase biochemical oxygen demand; introduce pathogens; and increase sedimentation, nutrients and contaminants through applications of the manure, fertilizers, and pesticides.

Predation

Predation of the sockeye occurs in the freshwater and marine environments. Christensen and Trites (2011) reviewed available literature on the predation. Smallmouth and largemouth bass as the well yellow perch are introduced species in the watershed, and are known to feed on salmonids, but little data exists regarding their impact on the sockeye (Christensen and Trites 2011). Hatchery wild salmon both compete with and directly prey upon sockeye (Appendix K 2009, Tatara and Berejikian 2011, Ruggerone et al. 2011), although impacts are not well documented in the Fraser Basin. Salmon enhancement facilities in the Fraser River Basin are listed below in the Appendix K. In addition to predation from hatchery fish, hatcheries are a source of potential contamination and have additional negative ecological effects on the salmon populations (see below, Buhle et al. 2009).

Climate Change

In British Columbia, minimum temperatures have increased 0.17°C per decade and precipitation has increased by 22% per century (Hinch and Martins 2011). Climate change has already caused

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earlier snowmelt in British Columbia rivers (Stewart et al. 2005), and water temperatures in the Fraser River have increased at a rate of 0.33°C per decade, increasing overall water temperature by about 2°C in the past 60 years (Chittendon et al. 2009). Lakes in the region are also warming, altering timing of spring ice break-up and lake turnover (Schindler et al. 2005).

Temperature related factors have also received a great deal of attention with respect to a marked increase in mortality during river migration and on spawning grounds (Hinch and Martins 2011).

- **Eggs**. Although sufficient data is lacking to thoroughly examine potential impacts of increased rainfall resulting from climate change, it is possible that increased rainfall is causing increased scour of redds, thereby decreasing overall egg survival (Hinch and Martins 2011).
- **Fry**. Temperature increases may be facilitating increased predation on lake-rearing sockeye fry (Hinch and Martins 2011).
- **Adult migrants**. Warmer river temperatures appear to decrease survival of adult migrants, particularly in early-run stocks, likely from a combination of exposure to temperatures above the 18¢C thermal tolerance, increased energy required for migration at higher flows, and combined higher metabolism in elevated temperatures (Eliason et al. 2011, Hinch and Martins 2011). Pathogens including *Parvicapsula minibicornis* also develop more quickly in warmer temperatures (Cooke et al. 2004, Crossin et al. 2009), increasing physiological stress and decreasing swimming performance of adult migrants (Bradford et al. 2010, Wagner et al. 2005). Earlier migration timing, likely related to elevated temperatures, has coincided with en route and pre-spawning mortality exceeding 90% in some years, impacting larger stocks and pushing already threatened stocks such as Cultus Lake to near extinction (Cooke et al. 2004). These trends are expected to increase as climate change progresses (Hague et al. 2011, Rand et al. 2006).

Marine environment near the Fraser River

Contaminants

The Strait of Georgia borders the British Columbia's main population centers of Vancouver and Victoria. About 80% of the marine pollution estimated to result from disposal of liquid waste from land-based activities (MOE 2006). Households generate about one-third of the waste and two-thirds is from industrial sources (MOE 2006). Despite increases in the populations of these areas (Johannes et al. 2011), contaminants in the Strait of Georgia have generally improved in recent decades. Best management practices including recycling programs and secondary or better water treatment have improved in recent years (Johannes et al. 2011). The past, however, lead, polychlorinated biphenyls (PCBs), mercury, dioxins and furans, tri-butyltin were documented at higher concentrations in the water, sediment, and marine birds and other biota in the Strait of Georgia (Johannes et al. 2011). Pulp and paper mills along the shores of the Strait were a major contributor of contaminants at least the 1980's when effluent treatment improved. In recent decades, polybrominated diphenylethers, personal care products and pharmaceuticals have increased in the Strait of Georgia (Johannes et al. 2011).

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Land/Marine Waters Use

Shipping and other marine vessels transport most goods and services across the coast, and may be a source of noise, emissions, accidental spills, and non-native species introductions through ballast water exchange, though Johannes et al. (2011) concluded that marine traffic has only limited direct interaction with sockeye habitat. Dredging covered the main navigation channel at the mouth of the Fraser River in recent years over the past 30 years, though dredging activities are limited to the periods sockeye salmon are not in the estuary (FREMP 2006). Dikes are extensive throughout the lower Fraser River estuary, causing an estimated 40% habitat loss in the area (Ellis et al. 2004), although construction has slowed in the recent decades and some have been removed to restore habitat (Johannes et al. 2011).

Predation

Significant marine predators of the Fraser River sockeye salmon may include spiny dogfish (*Squalus acanthias*), salmon sharks (*Lamna ditropis*), daggertooth (*Anatopterus nikparini*; Christensen and Trites 2001). Harbor seals (*Phoca vitulina richardsi*) and Steller sea lions (*Eumetopias jubatus*) are also common predators and have increased dramatically since their protection in the 1970 under the Fisheries Act (Forrest et al. 2009, Christensen and Trites 2001). Pacific herring (*Clupea harengus pallasi*) and Pacific cod (*Gadus macrocephalus*) are unlikely to prey on sockeye salmon smolts, but they are likely competitors for food in the Strait of Georgia and have been increasing in numbers in recent decades (Christensen and Trites 2001).

Many non-native introduced species in the Strait of Georgia prey upon and/or compete with Fraser River sockeye salmon. The Strait hosts an estimated 117 introduced species, more than twice the number found throughout the remainder of the Canadian west coast as a result of human population growth, aquaculture, and shipping activities (Johannes et al. 2011). The available data is inconclusive, recently documented Humboldt squid (*Dosidicus gigas*, Cosgrove 2005) may be a significant predator of the sockeye (Christensen and Trites 2001).

Christensen and Trites (2011) indicate that insufficient data exists to adequately identify key predators of the sockeye salmon and their overall impact, as well as understand the critical cumulative impact of the predation on the sockeye both marine and freshwater environments.

Climate Change

Major cycles associated with climate and sea surface temperature in the North Pacific Ocean, the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have exhibited pattern changes in the recent decades (Beamish 1999, Mantua et al. 1997). Marine habitat for Fraser River sockeye salmon, the Strait of Georgia and Gulf of Alaska,

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‹•ƒ„‘ –-ˈsäwÏ—™ƒ” ‡”-Šƒ ‹-™ƒ•xr› ‡ƒ”•ƒ‰‘ ♂ Chittenden et al. 2009), and salinity have decreased in the North Pacific (IPCC 2007). The period from the late 1980's to the present experienced warmer conditions than those during the previous period starting in 1940 (Figure 3, Johannes et al. 2011). Surface temperature (SST) has increased by 1.5 °C in the past 60 years (Chittenden et al. 2009). Warmer temperatures are coincident with blooms of harmful algae *Heterosigma*. *Heterosigma* blooms can cause salmon mortality through diminished respiratory function and ability to uptake oxygen (Rensel et al. 2010).

Figure 3. Temperature series of monthly surface temperature anomalies from the long-term mean from 1936–2009 from Entrance Island, central Strait of Georgia, (Johannes et al. 2011).

Temperature changes may also be causing decline zooplankton, primary source for rearing sockeye salmon (Figure 4, Johannes et al. 2011). Declines preferred plankton taxa coincide with increases of other species which sockeye may prey upon, although their food quality is considerably worth less fat content (El-Sabaawi et al. 2009). Overall, Johannes et al. (2011) conclude that warming temperatures coincide with declining food availability and quality, which may limit sockeye growth and decrease condition.

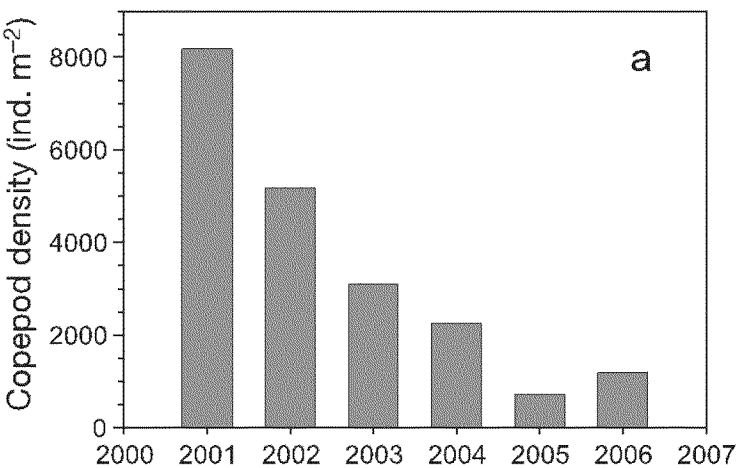

Figure 4. Declining zooplankton (*Neoclanus* sp.) abundance in the Strait of Georgia. (Johannes and MacDonald 2009).

Fisheries Management

Fraser River Management

Management of Fraser River sockeye and other salmon falls under myriad legal statutes. Due to international range of marine rearing sockeye, the fishery is subject to the

international Pacific Salmon Treaty between the U.S. and Canada and involving more than sixagencies (English et al. 2011).

Canada's main legal tool for sockeye salmon habitat conservation is Fisheries Act, in place since 1976. Attack knowledges the need to protect physical habitat for all life stages of sockeye, including their food sources and the quality of water in which they live (Johannes et al. 2011). Again, "net overall gain of habitat is to be achieved through limitation of development, restoration of lost damaged habitats, and salmonid 'enhancement' in the form of hatcheries and spawning channels. Many habitat restoration and compensation projects have been ineffective, however (Wilson 2003), hatcheries have unintended, negative ecological impacts on sockeye salmon (see below, Kostow et al. 2009).

Escapement targets, set annually under the Pacific Salmon Treaty by international panel, are complicated by cyclic nature of Fraser River stocks and resulting inter-annual variability in returns (English et al. 2011). Further, surement of actual escapement is complicated by route loss of sockeye (Figure 5). Escapement targets were not met for the Early Stuart sockeye from 2005–2009. While targets met, English et al. (2011) conclude that overharvest likely occurred in Early Stuart sockeye from 1984–2009, and for Early Summer sockeye from 1960–1989 (Figure 5).

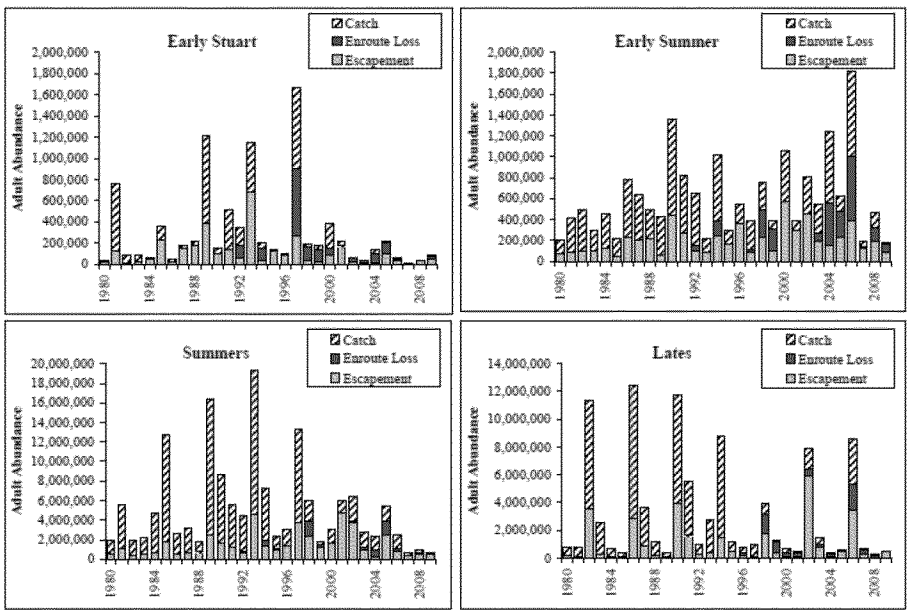

Figure 5. Estimates of total catch, escapement and enroute loss for Fraser sockeye by running group. Enroute losses were not estimated prior to 1992. English et al. 2011.

Bristol Bay Management

English et al. (2011) reviewed differences in management structure between Bristol Bay and the Fraser River and made the following conclusions. While Fraser River is subject to complex international management structure, management of Bristol sockeye falls

entirely within the Alaska Department of Fish and Game and four Area Management Biologists. The simpler structure of Bristol Bay management allows for changes in harvest regulations on day-to-day basis during the fishing season, while management decisions require a lengthier process for Fraser River sockeye. Mixed-stock fishing issues are also relatively minor in Bristol Bay due to the terminal nature of harvest fishing districts for nine stocks, compared to Fraser River with four run-timing groups which consist of more 25 stocks. Years are limited in Bristol Bay relative to the Fraser River. Further, the relatively escapement and low human populations in Bristol Bay region, recreational and subsistence fisheries in Bristol Bay amount to less 1% of total harvest, while First Nations and recreational allocations are much higher in more densely populated Fraser River. Bristol Bay's sockeye runs are also more concentrated, with a typical lasting six weeks compared to more three months on Fraser River. Overall, Bristol Bay benefits from a 'diversified portfolio' of stocks and life history types exploiting multiple large, productive rivers, resulting in extremely fisheries closures (Schindler et al. 2010). In contrast, Fraser River fisheries have been very limited or closed for six the last 20 years.

Wide fluctuations in sockeye returns to Fraser River (Figure 6) require managers to adjust goals every year, resulting in overharvest of stocks. Low-annual variability in returns allows Bristol Bay managers to use fixed escapement based on maximum sustained yield principles. Finally, escapement estimates in Bristol Bay are significantly more accurate than those in Fraser River owing to methodologies (tower counts and sonar upstream of each commercial fisheries in Bristol Bay vs. essentially one hydroacoustic site in Fraser River) and the fact that Bristol Bay fish are not subject to very high en route mortality, to which (up to 90%) Fraser River stocks are subject to between enumeration and spawning grounds.

Influences on Bristol Bay and Fraser River sockeye

Due to their economic importance and historically high returns, Bristol Bay and Fraser River sockeye salmon have been compared in recent months. Proponents of development in Bristol Bay use Fraser River as example of mining fisheries 'coexisting' (Joling 2011). However, despite watershed area of Fraser Basin more than doubling Bristol Bay's — Fraser River sockeye abundance pales in comparison (Figure 6). Further, though the Kvichak River listing as stock of concern (Morstad et al. 2010), Bristol Bay sockeye are not currently experiencing the types of declines exhibited in Fraser River. Possible reasons for these differences abound, and a few discussed below.

Figure 6. Bristol Bay (blue) and Fraser River (red) total runs (catch + escapement) since 1956. Averages for each river are indicated by the shading. Data from ADFG 2010 and DFO.

Habitat

Bristol Bay encompasses nine major watersheds and has a drainage of 92,000 km² (FBS 2011), while the Fraser River watershed drains 238,000 km² (Reynolds et al. 2006). Further, both basins are subject to opposite trends in productivity when Bristol Bay is experiencing high productivity, Fraser River and other U.S. West coast rivers experience lower productivity and vice versa (Mantua et al. 1997, Mantua and Hare 2002). The Bristol Bay basin was recently ranked as containing the most physically complex habitat throughout the range of Pacific salmon, making it most resilient to future impacts of climate change (Mantua and Francis 2004, FBS 2011) than most other Pacific watersheds supporting salmon, including the Fraser River (FBS 2011).

Aquaculture

In addition to management practices (reviewed by English 2011), it is important to note that major aquaculture activities in the Fraser River basin are in stark contrast to those in Bristol Bay, where aquaculture is prohibited. About 70 farms are located on the migration route of the Fraser sockeye salmon (Price et al. 2011). Although research is controversial, sea lice have been associated with increased transmission of sea lice and disease (Price et al. 2011, Miller 2011). Globally, survival or abundance is reduced near supporting aquaculture (Ford and Myers 2008). A review

potential impacts to Fraser sockeye from aquaculture activities is forthcoming (www.cohencommission.com).

Further, in response to population declines of Fraser sockeye, the Canadian government operates nearly 30 hatcheries basin (MacDonald et al. 2011, Appendix 1). Unintended effects of hatcheries include increased occurrence of disease (Naish et al. 2007), direct predation of wild by hatchery (Naman and Sharpe 2011), competition for food resources (Dittman et al. 2011 in press), space in freshwater environment (Tatara et al. 2008), in estuaries (Daly et al. 2011), and at sea (Ruggerone et al. 2011). The result of competition decreased productivity of wild salmon (Buhle 2009). Bristol does not support any salmon hatcheries, and salmon farming is prohibited in Bay and throughout the State of Alaska.

Human development

More than two-thirds of Bristol Columbians live in Fraser River Basin with an overall population of 2.73 million residents in 2006 (FBC 2010). Effects of human activities including urbanization, forestry, mining, agriculture, contaminants, introductions of non-native species, and other factors are widely considered to be a beneficial major factor in declines of salmon worldwide (Nehlsen et al. 1991, Hartman et al. 2006). Bristol Bay currently supports only about seventeen small communities, and a population of less than 5000 (DCRA 2010). At present, region does not support major industrial or other human activity. In contrast to water quality problems in Fraser River discussed above, available data for waters in Bristol Bay region indicate cold, well-oxygenated conditions with low concentrations of dissolved metals and other solutes (Zamzow 2010).

Cumulative impacts

The analysis conducted for the Cohen Commission is limited to potential causes of Fraser River sockeye declines within the past twenty years, during which declines became noticeable and commercially problematic (Pacific Salmon Commission data). Majority of reports released to date conclude that baseline and other pre-existing data is insufficient to examine the factors in question (Cooke et al. 2004, Christensen and Trites 2011, Hinch and Martin 2011, and others). Inquiry currently isolates individual potential factors in declines, failing to consider synergistic effects of all factors combined. Christensen and Trites (2011) conclude after their analysis of predation of sockeye salmon that "Cumulative threats are far more difficult to evaluate than a single factor. Because of Fraser sockeye salmon, stress from higher water temperatures, more in-kind competition due to increased escapement with resulting lower growth, and running the gauntlet through predators whose alternative prey may have diminished, may all have had cumulative effects. Assessing cumulative effects these and other stresses will require integrated evaluation." Peterman (2011) indicate that readers "should not necessarily expect to find single dominant cause of decline in Fraser sockeye." Finally, Healey (in press), in paper predicting Fraser sockeye response to climate change, indicates that the cumulative impacts of climate change across life stages

will be much greater than the impacts on individuals. He concludes that the impacts will also carry forward to the next generation, potentially leading to a downward spiral of productive capacity, " predicting a future Fraser River sockeye salmon not unlike that of major salmon rivers south of along the Pacific coast where salmon are extirpated from 40% of their former range (NRC 1996).

Conclusions

Fraser River sockeye salmon populations are suffering from a myriad of problems associated with urban and industrial development, leading to dramatic decreases in productivity, multiple fisheries closures, and federal and international population listings. In freshwater, contamination from mining, wood product and other industrial facilities, wastewater treatment plants, landfills, and salmon enhancement facilities (i.e., hatcheries and spawning channels) has led to contamination of 5000 sites, causing problems with pH, TSS, turbidity, nutrients, metals, phenols, personal care products, and pharmaceuticals. Introduced predators such as yellow and smallmouth bass, as well as hatchery fish may also impact Fraser River sockeye freshwater environment. And finally, increased river temperatures resulting from climate change are associated with higher mortality of sockeye route spawning grounds, likely due to increased physiological stress at higher temperatures, decreased swimming efficiency, and faster development of pathogens.

In the marine environment, industrialization and urban growth has led to contamination in the Strait of Georgia polybrominated diphenyl ethers, personal care products, and pharmaceuticals. Dredging and liking has reduced marine and estuarine sockeye habitat. Increased ship traffic is associated with accidental spills, noise, and introduction of non-native species. Warmer marine temperatures resulting from climate change are associated with more frequent harmful algal blooms, resulting in lower oxygen levels in the marine environment, as well as decreased plankton levels which are an important sockeye salmon food source.

Current efforts to understand Fraser sockeye declines is isolate potential causes, failing to consider the synergistic effects of combined stressors such as contaminants, used introduced predators, climate change, and others. Further, current analyses are forced to rely upon inadequate historical datasets, which fail to satisfactorily define baseline conditions.

Given their distinct physical and biological nature, as well as higher levels of urbanization and industrialization in Fraser River basin relative to Bristol Bay basin, recent comparisons between the two watersheds are suspect. However, comparing sockeye salmon populations alone, Bristol Bay—the world's largest sockeye salmon producing system—outnumbers the Fraser River by four times in watershed less than half its size. Indeed, the comparison between the two systems may simply highlight the inability of human development to coexist with salmon.

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Appendix 1. Salmon enhancement facilities in the Fraser River Basin. N/A = not available. (McDonald et al. 2011)

Area of Interest/Facility Name	Facility Type	Species Targeted	Organization
Cultus Lake			
Chilliwack River Hatchery	Hatchery	Chinook, Coho, Chum, and Steelhead	DFO Operations
Fraser Valley Trout Hatchery	Hatchery	Native and Domestic Rainbow Trout, Anadromous and Coastal Cutthroat Trout, and Steelhead Trout	Freshwater Fisheries Society of BC
Centre Creek Streamkeeper Program	Hatchery	N/A	Public Involvement Programs (Volunteer)
Harrison River			
Chehalis River Hatchery	Hatchery	Coho, Chinook, Chum, Steelhead and Cutthroat Trout	DFO Operations
Weaver Creek Spawning Channel	Spawning Channel	Sockeye, Chum, Pink	DFO Operations
Fee Creek Spawning and Rearing Channel	Hatchery	Coho	Public Involvement Programs (Volunteer)
Lower Fraser River			
Inch Creek Hatchery	Hatchery	Coho, Chinook, Chum, and Steelhead Trout	DFO Operations
Bell-Irving Kanaka Creek Hatchery	Hatchery	Chum, Coho, Pink, Steelhead, and Cutthroat Trout	Public Involvement Programs (Volunteer)
Beecher Creek Streamkeepers	Hatchery	Coho, Cutthroat, and Rainbow Trout	Public Involvement Programs (Volunteer)
Al Grist Memorial Hatchery	Hatchery	Coho, Chinook, and Pink	Public Involvement Programs (Volunteer)
Chilliwack River Action Committee (Trap Site)	Hatchery	Steelhead Trout, Coho, Chinook, Chum, and Pink	Public Involvement Programs (Volunteer)
Stave Valley Salmonid Enhancement Society	Hatchery	Coho and Chum	Public Involvement Programs (Volunteer)
Nicomen Slough Spawning Channel	Hatchery	Coho and Chum	Public Involvement Programs (Volunteer)
Musqueam Creek Project	Hatchery	Coho, Chum, and Cutthroat Trout	Public Involvement Programs (Volunteer)
Steveston High School Hatchery (on-site)	Hatchery	Coho and Chinook	Public Involvement Programs (Volunteer)
Cougar Creek Salmonid Enhancement Group	Hatchery	Coho	Public Involvement Programs (Volunteer)
Hoy Creek Hatchery	Hatchery	Coho	Public Involvement Programs (Volunteer)
River Springs Salmon Enhancement and Stream keepers	Hatchery	Coho, Chum, and Chinook	Public Involvement Programs (Volunteer)

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Area of Interest/Facility Name	Facility Type	Species Targeted	Organization
Lower Thompson River			
Spius Creek Hatchery	Hatchery	Chinook, Coho, and Steelhead Trout	DFO Operations
Loon Creek Hatchery	Hatchery	Rainbow Trout and Kokanee	Community Development Program Hatcheries
Deadman River Hatchery	Hatchery	Chinook and Coho	Community Development Program Hatcheries
Nechako River			
Nadina River Spawning Channel	Spawning Channel	Sockeye	DFO Operations
Spruce City Wildlife Fish Hatchery	Hatchery	Chinook	Public Involvement Programs (Volunteer)
North Thompson River			
Clearwater Trout Hatchery	Hatchery	Rainbow Trout and Kokanee Salmon	Freshwater Fisheries Society of BC
Dunn Lake Hatchery	Hatchery	Coho and Chinook	Community Development Program Hatcheries
Pitt River			
Upper Pitt River Hatchery	Hatchery	Chinook and Sockeye	DFO Operations
ALLCO Hatchery	Hatchery	Coho, Steelhead, Cutthroat, Pink, and Chinook	Public Involvement Programs (Volunteer)
Hyde Creek Hatchery	Hatchery	Coho and Chum	Public Involvement Programs (Volunteer)
Quesnel River			
Horsefly Spawning Channel	Spawning Channel	Sockeye	DFO Operations
Seton-Portage			
Gates Creek Spawning Channel	Spawning Channel	Pink	DFO Operations
Seton Creek Spawning Channels	Spawning Channel	Pink	DFO Operations
South Thompson River			
Shuswap River Hatchery	Hatchery	Chinook	DFO Operations
Kingfisher Community Hatchery	Hatchery	Coho, Spring, Sockeye, and Kokanee	Public Involvement Programs (Volunteer)
Adams River	Fishway	Sockeye	DFO Operations

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Area of Interest/Facility Name	Facility Type	Species Targeted	Organization
Upper Fraser River			
Penny Hatchery	Hatchery	Chinook	Community Development Program Hatcheries
Anderson Lake Fish Hatchery	Hatchery	Sockeye and Kokanee	Public Involvement Programs (Volunteer)
Hells Gate Fishways	Fishway	Sockeye, Coho, Pink, Chinook, Steelhead Trout	DFO Operations

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