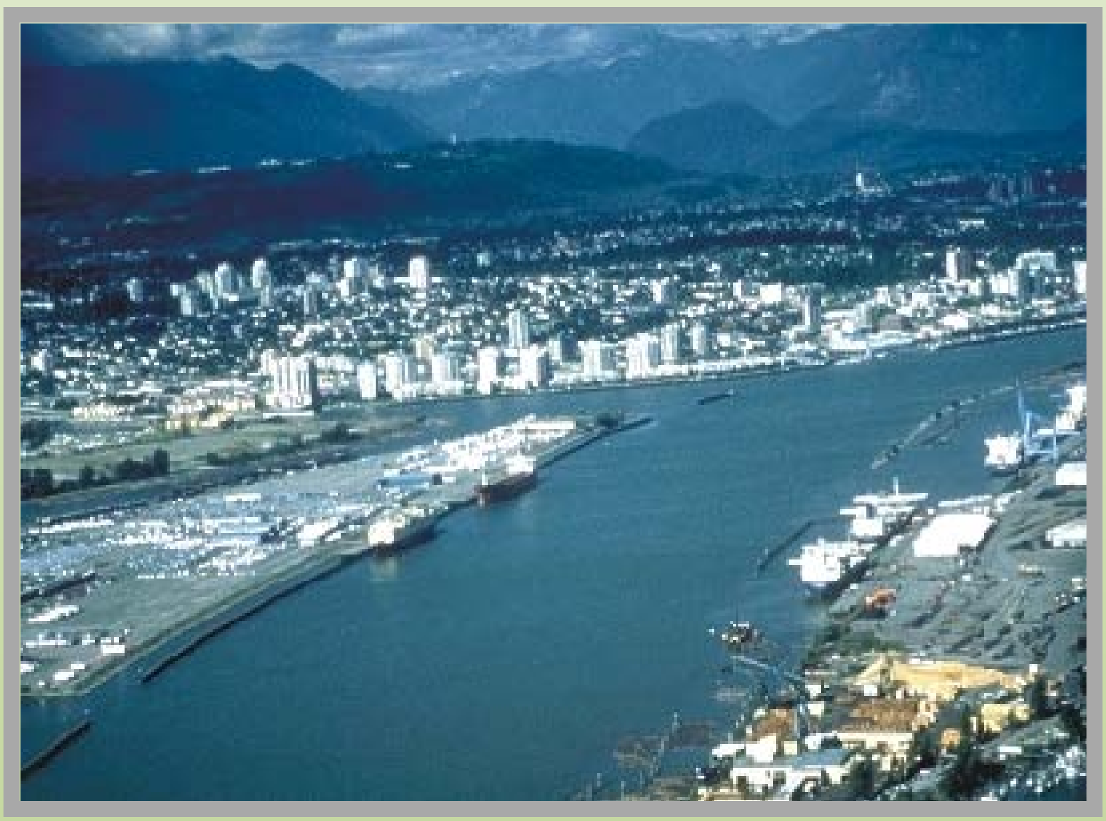
Canada's Fraser River

Reasons for sockeye salmon declines with a comparison to Bristol Bay

Sarah O'Neal
Dr. Carol Ann Woody
Fisheries Research and Consulting
www.fish4thefuture.com



22 August 2011

Table of Contents

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

Sarah O'Neal
Dr. Carol Ann Woody
Fisheries Research and Consulting
www.fish4thfuture.com

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 'co-existence' between mining and fisheries (Joling 2011). Due to their distinct physical and biological nature, as well as vastly different levels of urbanization and industrialization, the two systems make an unlikely comparison. However, the current state of the Fraser River system with impaired water quality, human development, changes in the predator and prey bases, and climate change has resulted in the lowest productivity of Fraser River sockeye in over 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 estuarine 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 any single direction, the current state of Fraser River sockeye is unfortunately another disastrous example of the co-existence of human development and salmon.

Status of Fraser River salmon

The Fraser River is known as one the greatest salmon rivers in the world and indeed is Canada's largest salmon producer (Burgner 1991). Sockeye salmon (*Oncorhynchus nerka*) 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 of sockeye, productivity (recruit per spawner), and commercial value suffered wide fluctuations, and ultimately significant declines (Pacific Salmon Commission data, 2011). Productivity is currently at an all-time low, indicating populations are barely replacing themselves (Figure 1, Peterman et al. 2010). Low returns resulted in fisheries closures in the last 6 of 11 years, including three consecutive years from 2007 to 2009, when total runs failed to exceed two million fish (Figure 1, Pacific Salmon Commission data).

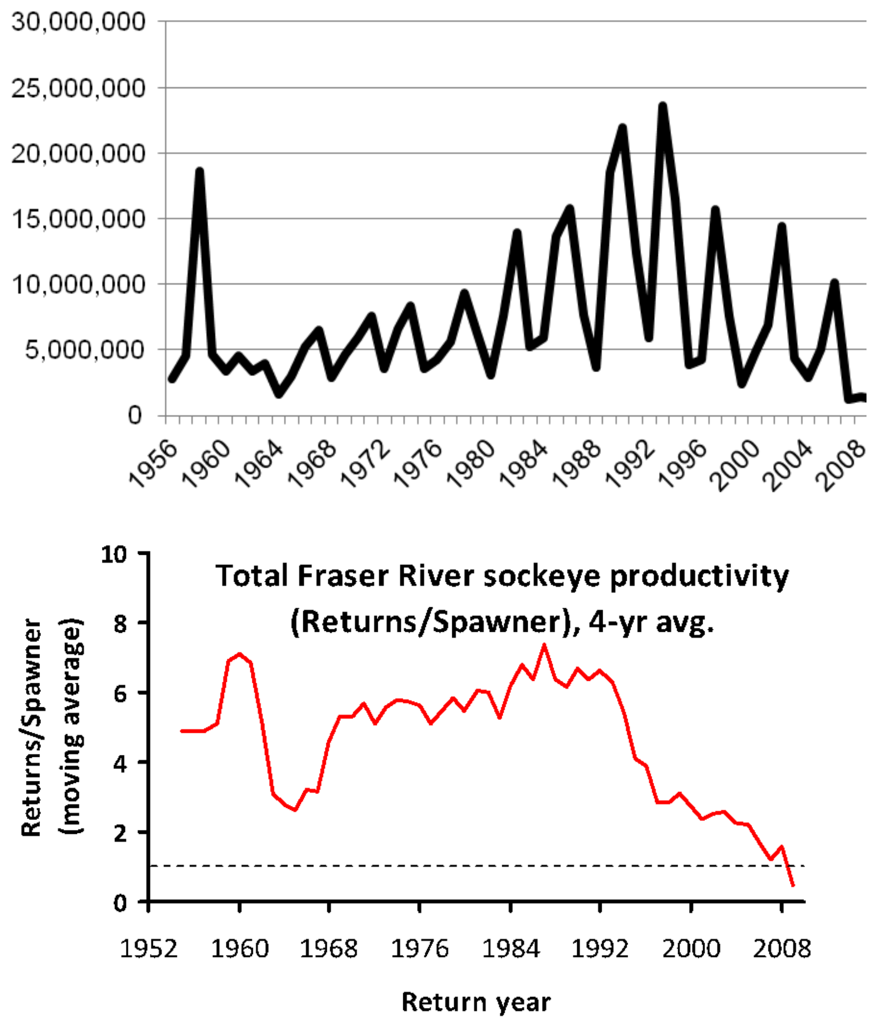


Figure 1. Total Fraser River sockeye returns (top) = harvest + escapement and four-year moving average of total adult returns per spawner across all Fraser River sockeye stocks (not including the minor jacks component) divided by total spawners 4 years before. The horizontal dashed line indicates the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

During the most recent conservation status review, the International Union for the Conservation of Nature (IUCN) categorized 5 of 11 Fraser River sockeye salmon stocks as threatened: one as Critically Endangered, three as Endangered, and one as Vulnerable

(Rand 2008). Cultus Lake sockeye salmon in the lower 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 the 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 the Fraser River sockeye declines, and concludes with a brief comparison of the 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 salmon. The study indicates contaminated surface water and sediment, as well as accumulation of contaminants in fish 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-tetrachlorodibezo-*p*-dioxin equivalents occurred in salmon eggs at concentrations that may adversely affect reproduction. Data were 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 likely a 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 and industrial landfills, several manufacturing facilities, as well as the oil and gas industry operate within the watershed (MacDonald et al. 2011). Many of the aforementioned 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 Canada's 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).

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 Fraser River sockeye salmon populations.

Mining

Several types of mining take place in the Fraser Basin (Figure 2): placer mining, gravel mining, industrial mineral production, metal mining, oil and gas production, and coal mining. At least one 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 mining is the dominant mining activity in the basin and may have the most significant impacts to salmon due to sedimentation effects (Nelitz et al. 2011).

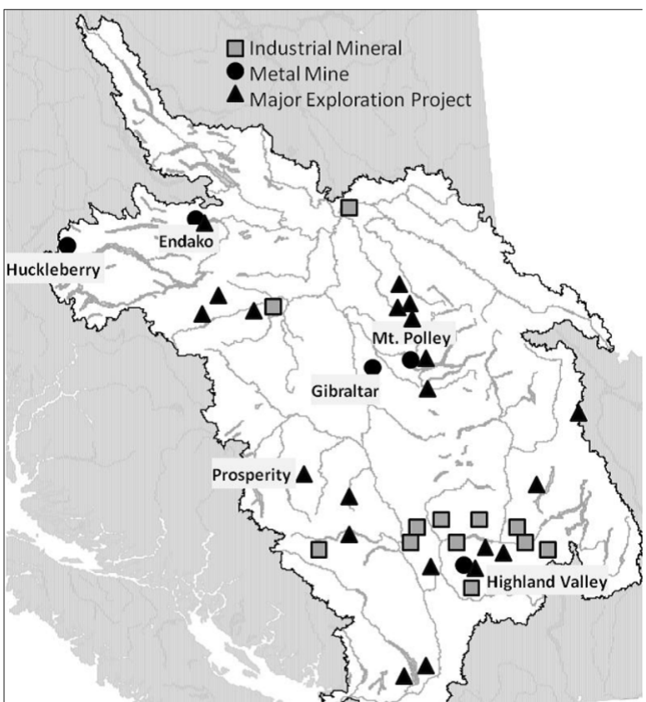


Figure 2. Distribution of the main categories of large mines in the Fraser River Basin. From Nelitz et al. 2011

Hydroelectric

Two large hydroelectric projects within the basin, the Bridge/Seton River power project and Alcan's Kemano Project on the Nechako River that affect water temperature and flow, at times inhibiting migration ability of sockeye salmon (Nelitz et al. 2001). Small scale hydropower projects, which can affect Total Gas Pressure (usually nitrogen supersaturation), gravel supply, and water temperature, also exist in the basein, though in fairly low numbers (about 20, Nelitz et al. 2011).

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 2-25% in municipalities upstream of Hope, 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 recent decades, there is more than one stream crossing per square-kilometer in some spawning areas and migration corridors (MOE 2008). Road crossings often serve as barriers to fish movement (Warren and Pardew 1998), an integral aspect of the life history of anadromous salmonids (Groot and Margolis . Further, up to 90% of the area in some watersheds was disturbed by 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 agriculture has increased in the past twenty years. Agriculture can cause physical alteration to streams, riparian zones, and floodplains; increase sedimentation and destabilize stream banks causing widening of stream channels; remove vegetation which can increase stream temperatures; compact soils subsequently increasing runoff; dewater groundwater sources important to maintenance of stream flows and temperature regimes; increase biochemical oxygen demand; introduce pathogens; and increase sedimentation, nutrients and contaminants through applications of manure, fertilizers, and pesticides.

Predation

Predation of sockeye salmon occurs in both freshwater and marine environments. Christensen and Trites (2011) reviewed available literature on predation. Smallmouth and largemouth bass as well as yellow perch are introduced species in the watershed, and are known to feed on salmon species, but little data exists regarding their impact on sockeye (Christensen and Trites 2011). Hatchery and wild salmon both compete with and directly prey upon sockeye (Appendix 1, Kostow 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 Appendix 1. In addition to predation from hatchery fish, hatcheries are a source of potential contamination and have additional negative ecological effects on wild 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 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 is bordered by British Columbia's main population centers of Vancouver and Victoria. About 80% of marine pollution is estimated to result through disposal of liquid and solid waste from land-based activities (MOE 2006). Households generate about one-third of that waste while two-thirds is from industrial sources (MOE 2006). Despite vast increases in the populations of those areas (Johannes et al. 2011), contaminants in the Strait of Georgia show a general improvement in recent decades. Best management practices including recycling programs and secondary or better water treatment have improved in recent years (Johannes et al. 2011). In the past, however, lead, polychlorinated biphenyls (PCBs), mercury, dioxins and furans, tri-butyl tin were documented at much higher concentrations in waters, 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 until 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).

Land/Marine Waters Use

Shipping and marine vessels transport most goods and services across the coast, and may be a source of noise, contaminants, 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 has lowered the main navigation channel at the mouth of the Fraser River by three meters over the past 30 years, though dredging activities are limited to periods when 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 that area (Ellis et al. 2004), although their construction has slowed in recent decades and some have been removed to restore salmon habitat (Johannes et al. 2011).

Predation

Significant marine predators of Fraser River sockeye salmon may include spiny dogfish (*Squalus acanthias*), salmon sharks (*Lamna diprosis*), and daggertooth (*Anatopterus nikparini*; Christensen and Trites 2011). Harbor seals (*Phoca vitulina richardsi*) and Steller sea lions (*Eumetopias jubatus*) are also common predators and have increased dramatically since their protection in 1970 under the Fisheries Act (Forrest et al. 2009, Christensen and Trites 2011). While Pacific herring (*Clupea harengus pallasi*) and cod (*Gadus macrocephalus*) are unlikely to prey upon sockeye salmon smolts, they are a likely competitor for food in the Strait of Georgia and have been increasing in numbers in recent decades (Christensen and Trites 2011).

Many non-native introduced species in the Strait of Georgia also 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 Canada's west coast as a result of human population growth, aquaculture, and shipping activities (Johannes et al. 2011). While available data is inconclusive, the recently documented Humboldt squid (*Dosidicus gigas*, Cosgrove 2005) may prove to be significant predators of sockeye smolts (Christensen and Trites 2011).

Christensen and Trites (2011) indicate that insufficient data exists to adequately identify key predators of sockeye salmon and their overall impact, as well as to understand the critical cumulative impact of predation overall on sockeye in both the 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 recent decades (Beamish 1999, Mantua et al. 1997). Marine habitat for Fraser River sockeye salmon, the Strait of Georgia and the Gulf of Alaska, is about 1.5˚C warmer than it was 60 years ago (Chittenden et al. 2009), and pH 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). Sea 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 the harmful algae *Heterosigma*. *Heterosigma* blooms can cause salmon mortality through diminished respiratory function and ability to uptake oxygen (Rensel et al. 2010).

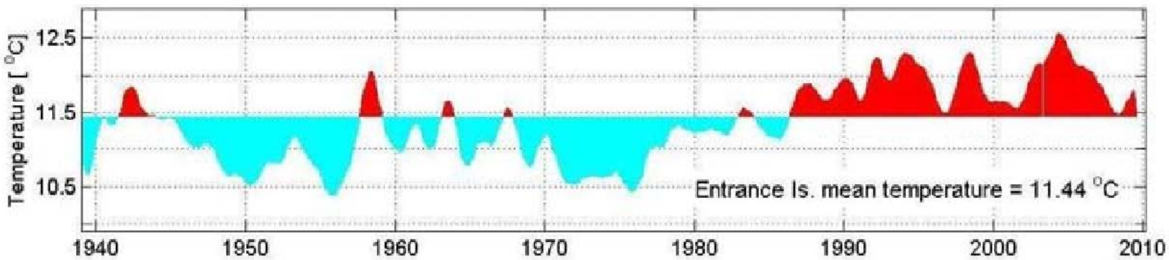


Figure 3. Long-term time series of monthly sea surface temperature anomalies from the long-term mean from 1936-2009 from Entrance Island, central Strait of Georgia, BC (From Johannes et al. 2011).

Temperature changes may also be causing a decline in zooplankton, a primary food source for rearing sockeye salmon (Figure 4, Johannes et al. 2011). Declines in preferred plankton taxa coincide with increases of other species which sockeye may prey upon, although their food quality is considerably lower with 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.

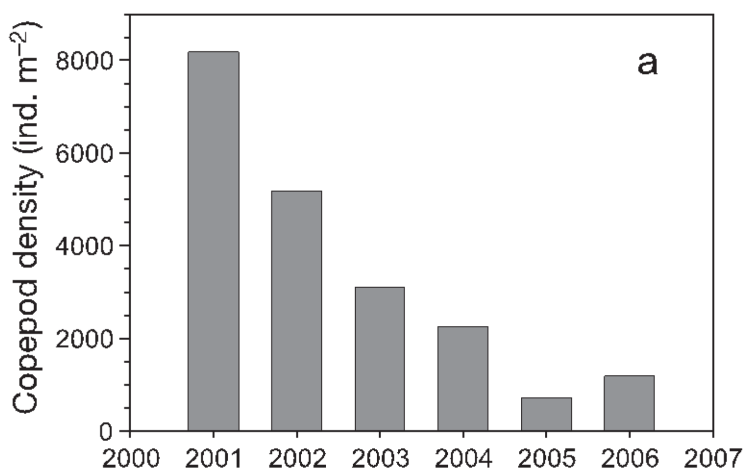


Figure 4. Declining zooplankton (*Neoclanus* sp.) abundance in the Strait of Georgia. From Johannes and MacDonald 2009.

Fisheries Management

Fraser River Management

Management of Fraser River sockeye and other salmon falls under myriad legal statutes. Due to the 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 six agencies (English et al. 2011).

Canada's main legal tool for sockeye salmon habitat conservation is the Fisheries Act, in place since 1976. The Act acknowledges the need to protect physical habitat for all life stages of sockeye, including their food sources and the quality of the water in which they live (Johannes et al. 2011). A "net gain" in overall acreage of fish habitat is to be achieved through limitation of development, restoration of lost or 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), and 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 an international panel, are complicated by the cyclic nature of many Fraser River stocks and resulting inter-annual variability in returns (English et al. 2011). Further, measurement of actual escapement is complicated by en route loss of sockeye (Figure 5). Escapement targets were not met for the Early Stuart sockeye from 2005-2009. While other targets were met, English et al. (2011) conclude that overharvest likely occurred in Early Stuart sockeye from 1984-2000, and for Early Summer sockeye from 1960-1989 (Figure 5).

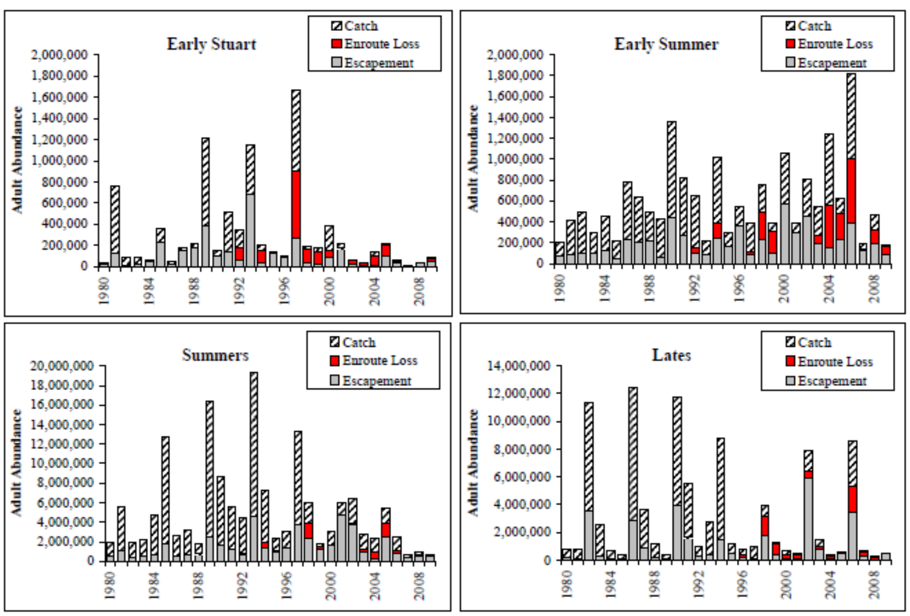


Figure 5. Estimates of total catch, escapement and en-route loss for Fraser sockeye by run-timing group. En-route losses were not estimated prior to 1992. From English et al. 2011.

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

Wide fluctuations in sockeye returns to the Fraser River (Figure 6) require managers to adjust goals every year, resulting in overharvest of some stocks. Low inter-annual variability in returns allows Bristol Bay managers to use a fixed escapement goal based on maximum sustained yield principles. Finally, escapement estimates in Bristol Bay are significantly more accurate than those in the Fraser River owing to methodologies (tower counts and sonar upstream of each of the commercial fisheries in Bristol Bay vs. essentially one hydroacoustic site in the Fraser River) and the fact that Bristol Bay fish are not subject to the very high en route mortality, to which some (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 the Fraser River as an example of mining and fisheries 'co-existing' (Joling 2011). However—despite watershed area of the Fraser Basin more than doubling Bristol Bay's—Fraser River sockeye abundance pales in comparison (Figure 6). Further, though the Kvichak River listing as a stock of concern (Morstad et al. 2010), Bristol Bay sockeye are not currently experiencing the types of declines exhibited in the Fraser River. Possible reasons for these differences abound, and a few are discussed below.

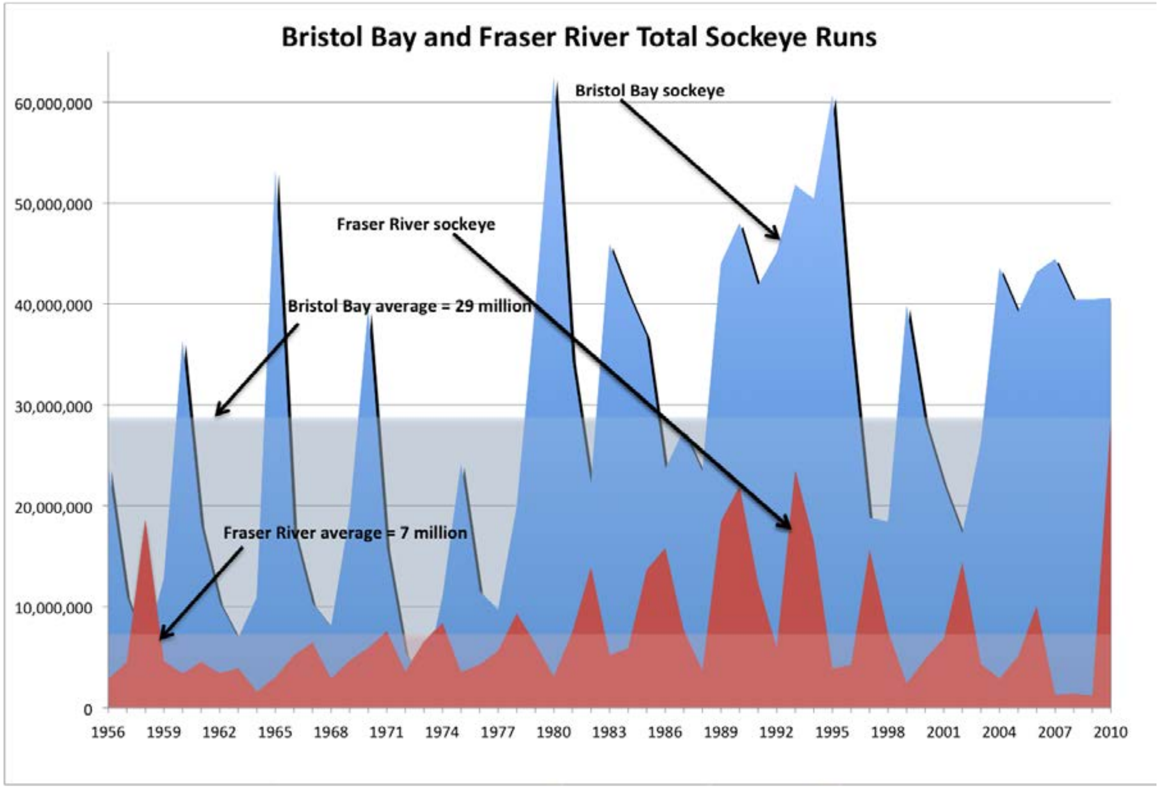


Figure 6. Bristol Bay (blue) and Fraser River (red) total runs (catch + escapement) since 1956. Averages for each river are indicated by shading. Data from ADFG 2010 and PSC.

Habitat

Bristol Bay encompasses nine major watersheds and has a drainage area of about 92,000 km^2 (FLBS 2011), while the Fraser River watershed drains 238,000 km^2 (Reynoldson et al. 2006). Further, the two basins are subject to opposite trends in productivity (i.e., when Bristol Bay is experiencing higher productivity, the 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 some the most physically complex habitat throughout the range of Pacific salmon, making it more resilient to future impacts of climate change (Mantua and Francis 2004, FLBS 2011) than most other Pacific watersheds supporting salmon, including the Fraser River (FLBS 2011).

Aquaculture

In addition to management practices (reviewed by English et al. 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 fish farms are located on the migration route of Fraser River sockeye salmon (Price et al. 2011). Although the research is controversial, farms have been associated with increased transmission of sea lice and disease (Price et al. 2011, Miller et al. 2011). Globally, marine survival or abundance is reduced in areas supporting aquaculture (Ford and Myers 2008). A review of potential impacts to Fraser River sockeye from aquaculture activities is forthcoming (www.cohencommission.com).

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

Human development

More than two two-thirds of British Columbians live in the 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 (if not the) 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, the region does not support major industrial or other human activity. In contrast to the water quality problems in the Fraser River discussed above, available data for waters in the 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). The majority of the reports released to date conclude that baseline and other pre-existing data is insufficient to thoroughly examine the factors in question (Cooke et al. 2004, Christensen and Trites 2011, Hinch and Martin 2011, and others). The inquiry currently isolates individual potential factors in declines, failing to consider the 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. In the case of Fraser River 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 the cumulative effects of these and other stresses will require integrated evaluation." Peterman et al. (2011) indicate that readers "should not necessarily expect to find a single dominant cause of the decline in Fraser sockeye." Finally, Healey (in press), in a 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 individual stages. 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 for Fraser River sockeye salmon not unlike that of major salmon rivers south of it 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 over 5000 sites, causing problems with pH, TSS, turbidity, nutrients, metals, phenols, personal care products, and pharmaceuticals. Introduced predators such as yellow perch and smallmouth bass, as well as hatchery fish may also impact Fraser River sockeye in the freshwater environment. And finally, increased river temperatures resulting from climate change are associated with higher mortality of sockeye en route to 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 by polybrominated diphenylethers, personal care products, and pharmaceuticals. Dredging and diking 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 zooplankton levels which are an important sockeye salmon food source.

Current efforts to understand Fraser sockeye declines isolate potential causes, failing to consider the synergistic effects of combined stressors such as contaminants, land use, 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 vastly higher levels of urbanization and industrialization in the Fraser River basin relative to the Bristol Bay basin, recent comparisons between the two watersheds are suspect. However, when comparing sockeye salmon populations alone, Bristol Bay—the world's largest sockeye salmon producing system—outnumbers the Fraser River by four times in a watershed less than half its size. Indeed, the comparison between the two systems may simply highlight the inability of human development to co-exist with salmon.

References

Angelo, M., P. Gallaugher, C. Orr, J. Reynolds, B. Riddell, and K. Wilson. 2010. Fraser sockeye 2010: Findings of a scientists' think tank. Speaking for the Salmon. 6pp.

Batten, S.D. and D.L. Mackas. 2009. Shortened duration of the annual *Neocalanus plumchrus* biomass peak in the Northeast Pacific.Marine Ecology Progress Series 393: 189-198.

Beamish, R.J., D.J. Noakes, G.A. McFarlane, L. Klyashtorin, V.V. Ivanov, and V. Kurashov.1999.The regime concept and natural trends in the production of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 56(3): 516-526.

Beamish, R.J. and C.M. Neville. 2001. Predation-based mortality on juvenile salmon in Strait of Georgia.. North Pacific Anadromous Fish Commission (NPAFC) Bulletin 2:11-13

Beauchamp, D.A. 1995. Riverine production on sockeye salmon fry migrating to Lake Washington. North American Journal of Fisheries Management 15(2): 358-365.

Bradford, M.J., C.P. Tovey, and L-M. Herborg. 2008. Biological risk assessment for yellow perch (*Perca flavascens*) in British Columbia. Canadian Science Advisory Secretariat.Research Document 2008/076, 23 pp.

Bradford, M.J., J. Lovy, and D.A. Patterson. 2010. Infection of gill and kidney of Fraser River sockeye salmon, *Oncorhynchus nerka* (Walbaum), by *Parvicapsula minibicornis* and its effect on host physiology. Journal of Fish Diseases 33: 769-779.

Buhle, E.R., K.K. Holsman, M.D. Scheuerell, and A. Albaugh. 2009. Using an unplanned experiment to evaluate the effects of hatcheries and environmental variation on threatened populations of wild salmon. Biological Conservation 142: 2449-2455.

Burgner, R.L. 1991. Life history of sockeye salmon (*Oncorhyhchus nerka*) pp. 1-119 in Groot, C. and L. Margolis (Eds.). Pacific Salmon Life Histories. UBC Press, Vancouver, British Columbia.

Cartwright, M.A., D.A. Beauchamp, and M.D. Bryant. 1998. Quantifying cutthroat trout (*Oncorhynchus clarki*) predation on sockeye salmon (*Oncorhynchus nerka*) fry using a bioenergetics approach. Canadian Journal of Fisheries and Aquatic Sciences 55: 1285-1295.

Chandler, P. 2010. Long-term temperature and salinity at BC lighthouses. Pp 49-51*in* W.R. Crawford, and J.E. Irvine (Eds.). State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009.

Chittenden, C.M., R.J. Beamish, and R.S. McKinley. 2009. A critical review of Pacific salmon marine research relating to climate. ICES Journal of Marine Science 66: 2195-2204.

Christensen, V. and A.W. Trites. 2011. Predation on Fraser River sockeye salmon. The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. 132 pp.

Clearly, J.S., J.F. Schweigert, and V. Haist. 2009. Stock assessment and management advice for the British Columbia herring fishery: 2009 assessment and 2010 forecasts. Canadian Science Advisory Secretariat Research Document 2009/079. 89 pp.

COSEWIC (Committee on the status of endangered wildlife in Canada). 2003. COSWEIC assessment and status report on the sockeye salmon *Oncorhynchus nerka* (Cultus population) in Canada. 66 pp.

Cooke, S.J., S.G. Hinch, A.P. Farrell, M.F. Lapointe, S.R.M. Jones, J.S. Macdonald, D.A. Patterson, M.C. Healey, and G. Van Der Kraak. 2004. Abnormal migration timing and high en route mortality of sockeye salmon in the Fraser River, British Columbia. Fisheries 29(2): 22-33.

Cosgrove, J.A. 2005. The first specimens of Humboldt squid in British Columbia.PICES Press. July: 30-31.

Crawford, W.R. and J.R. Irvine. 2010. State of physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2009. Department of Fisheries and Oceans Canadian Science Advisory Secretariat.Research Document 2010/053 viii + 137 p.

Crossin, G.T., S.G. Hinch, S.J. Cooke, M.S. Cooperman, D.A. Patterson, D.W. Welch, K.C. Hanson, I. Olsson, K.K. English, and A.P. Farrell. 2009. Mechanisms influencing the timing and success of reproductive migration in a capital breeding semelparous fish species, the sockeye salmon. Physiological and Biochemical Zoology 82(6): 635-652.

Daly, E.A., R.D. Brodeur, J.P. Fisher, L.A. Weitkamp, D.J. Teel, and B.R. Beckman. 2011. Spatial and trophic overlap of marked and unmarked Columbia River Basin spring Chinook salmon during early marine residence with implications for competition between hatchery and naturally produced fish. Environmental Biology of Fishes. Published online: 04 June 2011.

DCRA (Division of Community and Regional Affairs). 2010.Community Information Summaries (CIS). Alaska Community Database http://www.dced.state.ak.us/dca/commdb/cf_cis.htm. Accessed 10 August 2011.

DFO (Fisheries and Oceans Canada). 2003. Cultus Lake sockeye salmon stock status report. Fisheries and Oceans Canada, Pacific Region. 6 pp.

DFO. 2011. Commercial catch statistics. http://www.pac.dfo-mpo.gc.ca/stats/comm/index-eng.htm. Accessed 10 March 2011.

Dittman, A., D. May, M. Moser, D. Larsen, M. Johnston, and D. Fast. *In press.* Spatial and temporal overlap of hatchery and wild spring Chinook salmon spawning: Effects of hatchery acclimation sites. Environmental Biology of Fishes.

Eggers, D.M. and J.R. Irvine. 2007. Trends in abundance and biological characteristics for North Pacific sockeye salmon. North Pacific Anadromous Fish Commission (NPAFC) Bulletin 4: 53-75.

El-Sabaawi, R., J.F. Dower, M. Kainz, and A. Mazumder. 2009a. Characterizing dietary variability and trophic positions of coastal calanoid copepods: insight from stable isotopes and fatty acids. Marine Biology 156(3): 225-237.

El-Sabaawi, R., J.F. Dower, M. Kainz, and A. Mazumder. 2009b. Interannual variability in fatty acid composition of the copepod *Neocalanus plumbchrus* in the Strait of Georgia, British Columbia.Marine Ecology Progress Series 382: 151-161.

Eliason, E.J., T.D Clark, M.J. Hage, L.M. Hanson, Z.S. Gallagher, K.M. Jeffries, M.K. Gale, D.A. Patterson, S.G. Hinch, and A.P. Farrell. 2011. Differences in thermal tolerance among sockeye salmon populations. Science 332: 109-112.

Ellis, E., M. Church, and M. Rosenau. 2004. Characterisation of four secondary channels of the lower Fraser River. Habitat Conservation Trust Find Final Report. 188 pp.

English, K.K., T.C. Edgell, R.C. Bocking, M.R. Link, and S.W. Raborn. 2011. Fraser River sockeye fisheries and fisheries management and comparison with Bristol Bay sockeye fisheries. The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. 317pp.

Environment Canada. 2007. British Columbia and Yukon Territory water quality report (2001-2004): An application of the Canadian Water Quality. Index.Environment Canada. 82 pp.

Errington, J.C. and K.D. Ferguson. 1987. Acid mine drainage in British Columbia: Today and tomorrow. Proceedings of the 11th Annual British Columbia Mine Reclamation Symposium in Campbell River, BC, 1987. The Technical and Research Committee on Reclamation. 23 pp.

Farrell, A.P., S.G. Hinch, S.J. Cooke, D.A. Patterson, G.T. Crossin, M. Lapointe, and M.T. Mathes. 2008. Pacific salmon in hot water: Applying aerobic scope models and biotelemetry to predict the success of spawning migrations. Physiological and Biochemical Zoology 81(6): 697-709.

Fayram, A.H. and T.H. Sibley. 2000. Impact of predation by smallmouth bass on sockeye salmon in Lake Washington, Washington. North American Journal of Fisheries Management 20: 81-89.

FBC (Fraser Basin Council). 2010. The Fraser: A Canadian Heritage River. Fraser Basin Council in collaboration with the BC Ministry of Environment. 84 pp.

FLBS (Flathead Lake Biological Station). 2011. Riverscape Analysis Project. FLBS, University of Montana http://rap.ntsg.umt.edu/home. Accessed 10 August 2011.

Foote, C.J., and G.S. Brown. 1998. Ecological relationship between freshwater sculpins (genus *Cottus*) and beach-spawning sockeye salmon (*Oncorhynchus nerka*) in Iliamna Lake., Alaska.Canadian Journal of Fisheries and Aquatic Sciences 55: 1524-1533.

Ford, J.S. and R.A. Myers. 2008. A global assessment of salmon aquaculture impacts on wild salmonids. PloS Biology 6(2): e33. Doi:10.1371/journal.pbio.0060033.

Forrest, K.W., J.D. Cave, C.G.J. Michielsens, M. Haulena, and D.V. Smith. 2009. Evaluation of an electric gradient to deter seal predation on salmon caught in gill-net test fisheries. North American Journal of Fisheries Management 29(4): 885-894.

FREMP (Fraser River Estuary Management Plan). 2006. Environmental management strategy for dredging in the Fraser River Estuary. 47 pp.

Gallaugher, P. and L. Wood, Eds. 2010. Summit on Fraser River sockeye salmon: Understanding stock declines and prospects for the future. Speaking for the Salmon. 212 pp.

Grant, S.C.H., C.G.J. Michielsens, E.J. Porszt, and A. Cass. 2010. Pre-season run size forecasts for Fraser River sockeye salmon in 2010. Department of Fisheries and Oceans Canadian Science Advisory Secretariat.Research Document 2010/042, 12 pp.

Groot, C. and L. Margolis. 1991. Pacific salmon life histories. UBC Press. 564 pp.

Hague, M.J., M.R. Ferrari, J.R. Miller, D.A. Patterson, G.L. Russell, A.P. Farrell, and S.G. Hinch. 2011. Modeling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. Global Change Biology 17: 87-98.

Hare, S.R., N.L. Mantua, and R.C. Rancis. 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. Fisheries 24(1): 6-14.

Hartman, G.F., T.G. Northcote, and C.J. Cederholm. 2006. Human numbers: the alpha factor affecting the future of wild salmon. Pp. 261-292 *in* Salmon 2100: The Future of Wild Pacific Salmon, R.T. Lackey, D.H. Lack, and S.L. Duncan (Eds.). American Fisheries Society, Bethesda, MD.

Hinch, S.G. and E.G. Martins. 2011. A review of potential climate change effects on survival of Fraser River sockeye salmon and an analysis of interannual trends in en route loss and pre-spawn mortality. The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. 119 pp.

IPCC (International Panel on Climate Change). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and II to the Fourth Assessment. 104 pp.

Johannes, M.R.S., L.H. Nikl, R.J.R. Hoogendoorn, and R.E. Scott. 2011. Fraser River sockeye habitat use in the Lower Fraser and Strait of Georgia. The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. 117 pp.

Johannessen, S.C. and R.W. MacDonald. 2009. Effects of local and global change on an inland sea: the Strait of Georgia, British Columbia, Canada. Climate Research 40(1): 1-21.

Joling, D. 2011. Mine executive says Pebble, fishing can co-exist. Juneau Empire 04 March 2011.

Kistritz, R.U. 1994. Habitat compensation, restoration, and creation in the Fraser River estuary: Are we achieving a no-net-loss of fish habitat? Canadian Manuscript Report of Fisheries and Aquatic Sciences. 113 pp.

Kostow, K. 2009. Factors that contribute to the ecological risks of salmon and steelhead hatchery programs and some mitigating strategies. Reviews in Fish Biology and Fisheries 19(1): 9-31.

Levin, P.S., R.W. Zabel, and J.G. Williams. 2001. The road to extinction is paved with good intentions: negative association of fish hatcheries with threatened salmon. Proceedings of the Royal Society of London Series B: Biological Sciences 268: 1153-1158.

Levings, C.D. and D.J.H. Nishimura. 1997. Created and restored marshes in the lower Fraser River, British Columbia: summary of their functioning as fish habitat. Water Quality Research Journal of Canada 3: 599-618.

Luck, M., N. Maumenee, D. Whited, J. Lucotch, S. Chilcote, M. Lorang, D. Goodman, K. McDonald, J. Kimball, and J. Stanford. 2010. Remote sensing analysis of physical complexity of North Pacific Rim rivers to assist wild salmon conservation. Earth Surface Processes and Landforms 35: 1330-1343.

MacDonald, D., J. Sinclair, M. Crawford, H. Prencipe, and M. Meneghetti. 2011. Potential effects of contaminants on Fraser River sockeye salmon. The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. Technical Report 2: 164 pp. and appendices.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78(6): 1069-1079.

Mantua, N.J. and S.R. Hare. 2002. The Pacific Decadal Oscillation. Journal of Oceanography 35(1): 35-44.

Mantua, N.J. and R.C. Francis. 2004. Natural climate insurance for Pacific northwest salmon and salmon fisheries: finding our way through the entangled bank. *In* E.E. Knudsen and D. MacDonald (Eds.). Sustainable Management of North American Fisheries. American Fisheries Society Symposium 43: 127-140.

Martell, S.J.D., C.J. Walters, and R. Hilborn. 2008. Retrospective analysis of harvest management performance for Bristol Bay and Fraser River sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 65: 409-424.

Miller, K.M., S. Li, K.H. Kaukinen, N. Ginther, E. Hammill, J.M.R. Curtis, D.A. Patterson, T. Sierocinski, L. Donnison, P. Pavlidis, S.G. Hinch, K.A. Hruska, S.J. Cooke, K.K. English, and A.P. Farrell. 2011. Genomic signatures predict migration and spawning failure in wild Canadian salmon. Science 331: 214-216.

MOE (British Columbia Ministry of Environment). 1985. Ambient water quality assessment and objectives for the Fraser River sub-basin from Kanaka Creek to the mouth. Ministry of Environment, Government of British Columbia.

MOE. 2006. B.C. municipal solid waste tracking report. British Columbia Ministry of the Environment. 107 pp.

MOE. 2008. Environmental trends in British Columbia: 2007. British Columbia Ministry of the Environment. 367 pp.

Morstad, S., M. Jones, T. Sands, P. Salomone, T. Baker, G. Buck, and F. West. 2010. 2009 Bristol Bay area annual management report. ADFG, Division of Sport Fish and Division of Commercial Fisheries. 140 pp.

MPCA (Minnesota Pollution Control Agency). 2008. Endocrine disrupting compounds: A report to the Minnesota Legislature. 34 pp.

Muir, D.C.G., R.G. Shearer, J. Van Oostdam, S.G. Donaldson, and C. Furgal. 2005. Contaminants in Canadian arctic biota and implication for human health: Conclusions and knowledge gaps. Science of the Total Environment 351-352: 539-546.

Naish, K.A., J.E. Taylor III, P.S. Levin, T.P. Quinn, J.R. Winton, D. Huppert, and R. Hilborn. 2007. An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. Advances in Marine Biology 53: 61-194.

Naman, S. and C.S. Sharpe. 2011. Predation by hatchery yearling salmonids on wild subyearling salmonids in the freshwater environment: A review of studies, two case histories, and implications for management. Environmental Biology of Fishes. Published online: 27 April 2011.

Nehlsen, W., J.E. Williams, and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Nelitz, M., M. Porter, E. Parkinson, K. Wieckowski, D. Marmorek, K. Bryan, A. Hall, and D. Abraham. 2011. Evaluating the status of Fraser River sockeye salmon and role of freshwater eccology in their decline. The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. 236 pp.

NRC (National Research Council). 1996. Upstream: salmon and society in the Pacific Northwest. NRC, Committee on Protection and Management of Pacific Northwest Anadromous Salmonids, Board on Environmental Studies and Toxicology, Commission on Life Sciences. 452 pp.

Olesiuk, P.F. 2009. Abundance of Stellar sea lions (*Eumetopias jubatus*) in British Columbia. Canadian Science Advisory Secretariat: Research document 2008/063, 33 pp.

Pestal, G. and A. Cass. 2009. Using qualitative risk evaluations to prioritize resource assessment activities for Fraser River sockeye. Canadian Scientific Advisory Secretariat: Research Document 2009/071, Fisheries and Oceans Canada. 81 pp.

Peterman, R.M. and B. Dorner. 2011. Fraser River sockeye production dynamics. The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River. Technical Report 10: 133 pp.

Peterman, R.M. and F.Y.C. Wong. 1984. Cross correlations between reconstructed ocean abundances of Bristol Bay and British Columbia sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 42: 1814-1824.

Peterman, R.M., D. Marmorek, B. Beckman, M. Bradford, N. Mantua, B.E. Riddell, M. Scheuerell, M. Staley, K. Wieckowski, J.R. Winton, and C.C. Wood. 2010. Synthesis of evidence from a workshop on the decline of Fraser River sockeye. A Report to the Pacific Salmon Commission, Vancouver B.C. 246 pp.

Petersen, J.H. 2001. Density, aggregation, and body size of northern pikeminnow preying on juvenile salmonids in a large river. Journal of Fish Biology 58: 1137-1148.

Price, M.H.H., S.L Proboszcz, R.D. Routledge, A.S. Gottesfeld, C. Orr, J.D. Reynolds. 2011. Sea louse infection of juvenile sockeye salmon in relation to marine salmon farms on Canada's west coast. PLoS One 6(2): 1-9.

Rand, P.S. 2008. *Oncorhynchus nerka* (Fraser River). In: IUCN Red List of Threatened Species, www.iucnredlist.org. Version 2010.4.

Rand, P.S., C.P. Kellon, X. Augerot, M. Goslin, J.R. Irvine, and G.T. Ruggerone. 2007. Comparison of sockeye salmon (*Oncorhynchus nerka*) monitoring in the Fraser River Basin, British Columbia, Canada and Bristol Bay, Alaska, USA. North Pacific Anadromous Fish Commission (NPAFC) Bulletin 4: 271-284.

Rand, P.S., S.G. Hinch, J. Morrison, M.G.G. Foreman, M.J. MacNutt, J.S. MacDonald, M.C. Healey, A.P. Farrell, D.A. Higgs. 2006. Effects of river discharge, temperature, and future climates on energetics and mortality of adult migrating Fraser River sockeye salmon. Transactions of the American Fisheries Society 135: 655-667.

Rensel, J.E.J., N. Haigh, and T.J. Tynan. 2010. Fraser River sockeye salmon marine survival decline and harmful blooms of *Heterosigma akashiwo*. Harmful Algae 10(1): 98-115.

Reynoldson, T.B., J. Culp, R. Lowell, and J.S. Richardson. 2005. Fraser River Basin. Pp. 696-732 *in* Rivers of North America, A.C. Benke, A.C. and C.E. Cushing (Eds.). Elsevier Academic Press, Burlington, MA.

Roby, D.D., D.E. Lyons, D.P. Craig, K. Collis, and G.H. Visser. 2003. Quantifying the effect of predators on endangered species using a bioenergetics approach: Caspian terns and juvenile salmonids in the Columbia River estuary. Canadian Journal of Zoology 81: 250-265.

Ruggerone, G.T. and D.E. Rogers. 1992. Predation on sockeye salmon fry by juvenile coho salmon in the Chignik Lakes, Alaska: implications for salmon management. North American Journal of Fisheries Management 12: 87-102.

Ruggerone, G.T. and J.L. Nielsen. 2004. Evidence for competitive dominance of pink salmon (*Oncorhynchus gorbuscha*) over other salmonids in the North Pacific Ocean. Reviews in Fish Biology and Fisheries 14(3): 371-390.

Ruggerone, G.T., B.A. Agler, and J.L. Nielsen. 2011. Evidence for competition at sea between Norton Sound chum salmon and Asian hatchery chum salmon. Environmental Biology of Fishes. Published online: 07 June 2011.

Schindler, D.E., P.R. Leavitt, C.S. Brock, S.P. Johnson, and P.D. Quay. 2005. Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska. Ecology 86(12): 3225-3231.

Schindler, D.E., R. Hilborn, B. Chasco, C.P. Boatright, T.P. Quinn, L.A. Rogers, and M.S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465: 609-612.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. Changes toward earlier streamflow timing across Western North America. Journal of Climate 18: 1136-1143.

Tatara, C.P., S.C. Riley, and J.A. Scheurer. 2008. Environmental enrichment in steelhead (*Oncorhynchus mykiss*) hatcheries: field evaluation of aggression, foraging, and territoriality in natural and hatchery fry. Canadian Journal of Fisheries and Aquatic Sciences 65: 744-753.

Tovey, C.P., M.J. Bradford, and L-M. Herborg. 2008. Biological risk assessment for smallmouth bass (*Micropterus dolomieu*) and largemouth bass (*Micropterus salmoides*) in British Columbia. Canadian Science Advisory Secretariat Research Document 2008/075. 47 pp.

Veldhoen, N., M.G. Ikonomou, C. Dubetz, N. MacPherson, T. Sampson, B.C. Kelly, and C.C. Helbing. 2010. Gene expression profiling and environmental contaminant assessment of migrating Pacific salmon in the Fraser River watershed of British Columbia. Aquatic Toxicology 97: 212-225.

Wagner, G.N., S.G. Hinch, L.J. Kuchel, A. Lotto, S.R.M. Jones, D.A. Patterson, J.S. Macdonald, G. Van Der Kraak, M. Shrimpton, K.K. English, S. Larson, S.J. Cooke, M.C. Healey, and A.P. Farrell. 2005. Metabolic rates and swimming performance of adult Fraser River sockeye salmon (*Oncorhynchus nerka*) after a controlled infection with *Parvicapsula minibicornis*. Canadian Journal of Fisheries and Aquatic Sciences 62: 2124-2133.

Warren, Jr., M.L. and M.G. Pardew. 1998. Road crossings as barriers to small-stream fish movement. Transactions of the American Fisheries Society 127: 637-644.

Wilson, P.H. 2003. Using population projection matrices to evaluate recovery strategies for Snake River spring and summer Chinook salmon. Conservation Biology 17(3): 782-794.

Winship, A.J., and A.W. Trites. 2003. Prey consumption of Stellar sea lions (*Eumetopias jubatus*) off Alaska: How much prey do they require? Fishery Bulletin 101(1): 147-167.

Zamzow, K. 2010. Surface water quality near the proposed Pebble Mine, Alaska, 2009-2010: Nushagak, Kvichak, and Chulitna drainage headwaters. Center for Science in Public Participation.

Appendix 1. Salmon enhancement facilities in the Fraser River Basin. N/A = not available. From MacDonald 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)

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

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