FROM PRISTINE TO POLLUTED

HOW CHEMICALS AND POLLUTANTS DRIVE

FISHERY DECLINES AND ECOSYSTEM COLLAPSE

Case Study:

Fraser *(Stó:lō)* River

Canada

March 2024

FROM PRISTINE TO POLLUTED: HOW CHEMICALS AND POLLUTANTS DRIVE FISHERY DECLINES AND ECOSYSTEM COLLAPSE. CASE STUDY: FRASER (Stó:lō) RIVER, BRITISH COLUMBIA, CANADA

Author: Dr. Matt Landos, BVSc (Hons I) MANZCVS, Director, Future Fisheries Veterinary Service Pty Ltd., Associate Researcher, Sydney University, Faculty of Veterinary Science

March 2024

IPEN is a network of over 600 non-governmental organizations working in more than 125 countries to reduce and eliminate the harm to human health and the environment from toxic chemicals.

www.ipen.org

National Toxics Network (NTN) was a not-for-profit civil society network striving for pollution

reduction, protection of environmental health and environmental justice for all. NTN was committed to a toxics-free future.

ISBN: 978-1-955400-18-3

Cite this publication as:

Landos, M. (2024). *From Pristine to Polluted: How Chemicals and Pollutants Drive Fishery Declines and Ecosystem Collapse. Fraser (Stó:lō) River, British Columbia, Canada*. International Pollutants Elimination Network.

ACKNOWLEDGMENTS

IPEN would like to acknowledge that this document was produced with financial contributions from the Government of Sweden and other donors. The views herein shall not necessarily be taken to reflect the official opinion of the donors.

Author's Preface

My family have given me tremendous support and opportunity in my life. School holidays were always a chance to escape suburbia and be immersed in nature. Often times we'd go somewhere by the water, be it a river, a lake or the ocean beaches. At every opportunity I had a fishing rod in hand, with high hopes for capturing a big fish, but even small fish were enthralling to me.

My Mum was a radiography nurse with an interest in science and biology that I came to share with her. My Dad was a public servant working in quarantine inspection service with an economics background. Interactions with veterinary scientists at my Dad's work, were formative in influencing my thinking through high school and direction to University.

My interest in aquatic animals continued to grow, but rather than embark on a marine biology degree I chose to explore my interests through a veterinary degree at University of Sydney. Through the undergraduate degree the science of animal health and food production captured my mind and upon graduation I launched into a rural job that spanned dairy cattle, birds, cats and dogs. It was another five years later with an injured back from pulling out calves and repairing injured hooves that my original visions of becoming a fish veterinarian returned.

I was very lucky to again have good fortune shine on me and I commenced work for the State Government as a fish veterinarian at a regional laboratory. The lab was stacked with immensely skilled veterinary pathologists to whom I owe a great debt for their patience in imparting their knowledge to me. The job involved investigating the causes of fish kills and fish disease all around the State, embracing both field work and laboratory diagnostics. The role also had a biosecurity policy component. It was a slow dawning through this time, that all was not well with the health of the rivers. Expanding knowledge helped me recognize there were multiple threats. It became clear to me that disease in aquatic animals was tightly associated with the health of the environment in which they lived.

In wild capture fisheries the media and conservation group narratives were focused on over-fishing. Fisheries management also focused on catch as the dominant influence on fishery productivity - declines were regularly attributed to too much fish being caught. Correspondingly, management responses sought to reduce catches through implementing a range of measures like size limits, bag limits, closed seasons, marine protected areas, license buy-backs, restocking and quota. The effects of the degrading water quality and habitat were not given the same consideration. This struck me as being inconsistent with the evidence of disease expression and mortality incidents which had nothing to do with fishing activities.

Dr Mariann Lloyd Smith, founder of the National Toxics Network (NTN) and member of International Pollutants Elimination Network (IPEN) and Joanna Immig connected with me to co-author the report, Aquatic Pollutants in Oceans and Fisheries**.** Following this endeavor, IPEN supported me, through NTN, with a team of co-authors and editors to produce three case studies: Richmond River, NSW, Australia; Mekong River, Vietnam; and Fraser River, British Columbia, Canada. These case studies explore a history water pollution brought by changes to land-use and changes of pollution governance over time. Each case study gives insight to the current day circumstances and offers up pathways for restoration. A synthesis report brings together common themes from the three cases studies.

I hope that humanity can quickly learn from the global body of science and haphazard pollution governance through time, to achieve restoration of aquatic ecosystems. To do this, relies in no small part, on our ability to control the water pollution we generate.

Matt Landos

Table of Contents

Introduction

The Fraser River is the largest in British Columbia, and the third largest by discharge volume in Canada. First Nations and Inuit people were the first who lived in the Fraser Basin on Canada's west coast. While their languages, beliefs and stories of creation are specific to each First Nation there is a unifying theme that "everything is one and all is interconnected. Humans, animals, nature, and the spirit world are all tied together in a mystical circle, connecting those who came before, those who live now, and those who will come in the future." (The Fraser Basin Council, 2013).

Within the Fraser Basin, it is Canada's largest river, the Fraser, which is the source of life that connected the First Nations living there. The Coast Salish people lived where the Fraser River spills into the Strait of Georgia down to Puget Sound in the south. They call the Fraser River Stó:lō. Under First Nations management the ecosystem and fisheries of the Stó:lō remained abundant for thousands of years prior to colonial settlement. The impacts since colonial settlement now deprive First Nations people of the ability to harvest traditional marine foods which they had been reliant upon for more than a millennia prior (Chisholm, 1986) (Lepofsky, Trost, & Morin, 2007).

The Fraser River tracks 1375 kilometers from its source to meet the Salish Sea within the Pacific Ocean just south of the city of Vancouver in British Columbia. The catchment is around 220,000 hectares. Around 3 million people live in this catchment within British Columbia. The river has the largest annual flow of all Canadian rivers which empty into the Pacific northwest with 3,475 cubic meters of average flow per second, or 113 cubic kilometers of freshwater per year. Around 20 million tonnes of sediment are transported to the ocean annually to the river delta where it joins the Strait of Georgia.

The diversity of fish in the Fraser River is relatively limited compared to other major rivers like the Mekong River. There are around 36 species of freshwater fish and 18 anadromous species which are transitory, migrating up the river from the sea to spawn (Richardson & Healey, 1996).

Assessing what constitutes a healthy Fraser River is incredibly challenging for scientists and public policy makers in their efforts to achieve a desired notion of 'sustainability' in the context of other policy agendas. The approach taken in this report is to firstly examine the history of First Nations relationships with the salmon fishery, before detailing the history of land use changes wrought by colonial settlement, industry, and population expansion. The contribution of the aquatic pollution consequences from each activity on the health and productivity of the fishery are then able to be considered, in light of attempts to regulate the sources of pollutants. In essence, fishery productivity is considered a useful proxy for Fraser River health.

The arrival of colonialists brought a different value system to the First Nations people. This socioeconomic reframing of human's interactions with nature resulted in a rapid transformation of the landscape, in essence it was an industrial conversion of public natural resources into private export commodities to feed the economic development of the region. Regulations were geared to promote maximum exploitation of resources.

Through to the 1990's the river had supported one of the world's largest wild salmon fisheries, albeit significantly reduced from levels of the late 1800's when colonial commercial exploitation began (Merriam, 1954). The recent demise of the fishery is the collective result of many impacts that ultimately reduced the functionality of the ecosystem which had previously supported the highly productive fishery. In the rush for economic gains, a failure to understand, value and protect the ecosystem which supported the harvestable natural resources has taken place.

The impacts of early colonial fishing practices, pollution and habitat destruction are not well documented in recent scientific literature (Morin & Evan, 2022), resulting in a case of shifting baseline syndrome (Pauly, 1995) where later research can under-appreciate a baseline from before the commencement of their contact with the fishery. While there were fishery management reports from the 1880s, the practice of considering fishery ecology did not begin in earnest until the 1970s.

Regulations deployed by the different levels of Government (municipal, provincial, and federal) over time are reviewed through the lens of their success (or otherwise) of achieving their stated aims of protection of water quality and fisheries from pollution impacts. The dominant thinking embedded in pollution control policy from colonial times was that the rivers and oceans represented natural resources to assimilate industrial and domestic wastes, and as such, should be exploited to maximize economic benefits to industry.

While more recent policy has endeavored to better control pollution through more comprehensive planning and protection of water, the implementation is still conflicted by land tenure and a political reluctance to threaten economic outcomes of industries in the era of privatization and globalization. With a shift to industry self-regulation under a mantra of risk management for waste discharges from 2003, it is evident substantial challenges to restore and protect water quality remain.

The marine ecology of the area was already badly degraded by the middle of the 20th century (Morin & Evan, 2022). Today the stocks of salmon returning to the Fraser River, even with substantial efforts of hatcheries to restock the system, have collapsed down to less than 5 % of their formerly colossal biomass, with several wild salmon runs now gone altogether.

As early as 1870 overfishing triggered whale population decline in inlets adjacent the Fraser River's termination into the Strait of Georgia. Pollution and habitat loss also contributed to the collapse of local herring stocks in 1885, eulachon in 1899 and smelt in the 1930s likely impacting the function of the entire regional aquatic ecosystem due to the loss of both forage fish biomass and predators.

More than one hundred and fifty years of accrued colonial-led regulation on the fishery and the environment it relies upon, has yet to prove sufficient to begin to restore the stocks of salmon and other fish of the Fraser River. Historic legacy and ongoing pollution are continuing to play a significant role inhibiting its recovery.

Pacific Salmon

The most well-known fish of the region are the five species of Pacific salmon: Sockeye salmon (*Oncorhynchus nerka*); Pink salmon (*Oncorhynchus gorbuscha*); Chum salmon (*Oncorhynchus keta*); Chinook salmon (*Oncorhynchus tshawytscha*); and Coho salmon (*Oncorhynchus kisutch*). The sockeye salmon has been the most abundant of the salmon species in the Fraser River. The extraordinary abundance of Pacific salmon species and habit of traversing all the way up rivers to spawn, before juveniles swim back to the ocean to feed and grow, made them a valued and readily accessible food resource for First Nations peoples, as well as wildlife like bears and eagles and later commercial exploitation by colonial settlers.

The salmon fishery is possibly the most researched and most managed on the planet. Scientists have invested a huge effort to understand the various impacts on the productivity of salmon. Part of this knowledge generation has included measurement of: catches; counts of returning spawning fish to their various spawning locations; numbers of surviving juveniles exiting the rearing lake areas; habitat assessment; prey species; predators; water quality parameters; migration routes and oceanic conditions.

Biology of Pacific salmon

Salmon lay their eggs on the bottom of freshwater rivers or lakes in clean gravel beds. The young sockeye salmon hatch and typically remain in freshwater lakes for their first two to three years of life. They then make their way to the outlet of the Fraser River at Vancouver. Where the freshwater mixes with the salt on tidal mudflats, saltmarsh and through eel grass the early life stages find shelter and food before they head out into the Strait of Georgia at 75-90mm to feed initially on zooplankton before venturing northwards through the Discovery Islands to the Johnstone Strait and past the Broughton archipelago into the Pacific Ocean to feed and grow to adulthood. The marine phase typically lasts two or sometimes three years, before the fish in spawning condition return to the distinct sub-catchment of the Fraser River they came from. Over 10,000km can be traversed in that time (MacDonald, et al., 2020).

Mortality in the marine phase can be up to 2-4% during the first 40 days before declining to 0.4-0.8% per day for sockeye salmon (Christensen & Trites, 2011).

Each distinct area produced its own run of salmon, which tended to migrate at slightly different times in the season and were often remarkably genetically distinct.

Species of salmon	**Freshwater juvenile phase duration**	**Marine phase duration before return to freshwater to spawn**
Pink salmon	Few weeks	1-2 years
Chum salmon	Few weeks	2-3 years
Chinook salmon	Up to one year	2-7 years
Sockeye salmon	1 to 3 years	2-3 years
Coho salmon	1 to 2 years	Up to 1.5 years

Pink salmon have the shortest life cycle consisting of distinct even and odd year runs and of all the salmon have the highest rates of straying to return to different rivers from where they were born.

Some coho salmon stay in local marine waters rather than traveling the open ocean as the other salmon species do (Beamish R. , et al., 2007) (Saskida, 2015).

The movement of salmon from the sea into the upper freshwaters has potential to transport contaminants acquired in marine phase to the freshwater spawning locations. Additionally, as the fish migrate up to spawn, they may energetically consume body fats (lipids), leading to mobilization of lipid-stored pollutants such as PCBs, dioxins, furans, mercury and PBDEs thereby increasing exposures to the gametes (sperm and ova) immediately prior to spawning. When the broodfish die post-spawning their contaminant load can be released into the freshwater food webs leading to exposures for other resident species (Ewald, Larsson, Linge, Okla, & Szarzi, 1998). The out-migration of juvenile sockeye salmon from freshwater can shift 3-30% of the imported mercury back out of the freshwater environment (Baker, Schindler, Holtgrieve, & St Louis, 2009).

Nothing is wasted in a functioning ecosystem (Semeniuk, 2003). After spawning, the annual natural death of salmon in the rivers releases nutrients which support productivity in the river. Around half of the nutrient used by hatching salmon, can be traced to the releases from their parents.

The natural functioning ecosystem sees transport of nutrients, embodied with the migratory fish moving from the marine ecosystem well into the freshwater catchments. The activities of bears move the nutrients further into the riparian landscape nourishing vegetation growth (Semeniuk, 2003). This nutrient enrichment supports faster and larger tree growth alongside waterways (Reimchen & Fox, 2013), which in turn supports improved habitat in the streams, by supplying large woody debris, filtration and trapping of sediment and offering shade to keep waters cool.

The tributaries of the lower Fraser River provide critical habitat to 65% and 85% of Fraser coho and chum salmon stocks who spawn in these streams. The Fraser's largest runs of chinook, coho and chum salmon and the third largest pink salmon run utilize the Harrison-Lillooet watershed lakes and side channels in the lower Fraser River. The access and health of these lower river waters are essential for feeding and rearing juveniles salmon and other species (Nener & Wernick, 1997). All the pacific salmon pass through the lower Fraser River twice- once as juveniles as they swim to sea, and again as adults returning to spawn in the catchment tributaries.

First Nations history of use and management of Fraser River fishery resources

Around 29 First Nations communities, collectively referred to as Stó:lō, have lived a subsistence existence in the Fraser River basin for more than 10,000 years. Their population was estimated to be around 20,000-60,000 at the time of colonial settlement in the 1850's. The earliest fossil records suggest First Nations people were actively salmon fishing from at least 7500 years ago in the Thompson River tributary of the Fraser River (Lichatowich, 1999).

Stó:lō is both the Indigenous name for Fraser River and the collective name for the many First Nations in the Lower Fraser Valley.

First Nations citizen, Sonny McHalsie put it simply "*We are the river, and the river is in us*"[1].

In 1993 the Assembly of First Nations noted that- "*Even though we represent many different First Nation cultures and traditions, we all agree on one basic teaching: We were put here by the Creator to care for this land we call Mother Earth. This means we have a responsibility to maintain good relations with all of her creation.*"

The First Nations people governed their fisheries, prior to arrival of colonial Europeans with a complex array of oral stories, ceremonies and lived experience passed on from family and tribe members which generated a profound respect for the fish. They believed that all living things were once people and should be treated with the same respect as their own relatives.

It was believed that the runs of salmon were lineages, and if some were allowed to return to their home rivers, then those lineages would always continue. Out of respect, when the first large sockeye was caught, a First Salmon Ceremony was conducted where the fish would be placed on a bed of boughs to introduce it to the Elder using intricately decorated wooden rods. This was the WSÁNEC way to greet and welcome the king of all salmon. The celebration would last up to ten days. While taking this time to celebrate it allowed a major portion of the salmon stocks to elude First Nations capture and return to their rivers to spawn, thereby sustaining those lineages or stocks (Claxton, 2008).

First Nations people utilised fishing equipment such as weirs (Figure 3), basket traps, dip nets (Figure 1, Figure 2), gaffs, seine nets and spears to catch sturgeon, cod, trout, eulachon and salmon. These were environmentally non-destructive fishing methods. They did not contribute to habitat damage

[1] https://www.theglobeandmail.com/news/national/the-story-of-the-fraser-river-a-symbol-of-life-that-can-also-be-violent-and-deadly/article31403733/

unlike early colonial use of explosives, or later use of bottom trawlers, and pollutants from the use and combustion of petrochemicals that were central to post-colonial fishing.

Salmon were prized above all other fish and were the economic, cultural, and spiritual heart of First Nations in the Fraser River Basin (The Fraser Basin Council, 2013). Harvesting also took place at river mouths where salmon congregated and were captured using tidal stone traps and reef nets woven of willow, cedar, and dune grass. Harvesting of other species like herring, sturgeon, smelt, eulachon, and shellfish were also important.

Figure 1: First Nations Fishing for salmon with dip net. Image D-06014 courtesy of Royal BC Museum, BC Archives

Figure 2: First Nations women fishing in shallow water with nets in the Fraser River. City of Richmond Archives, 1977 16 12.

Such equipment allowed tribes to closely monitor the salmon populations. Through time harvesting agreements were established between house groups from different territories, along the river with elders making decisions about who could access fishing spots, when they would be utilized and how much fish it would be necessary to catch to store enough to support the entire family group.

Figure 3: Typical type of First Nations salmon weir. Source: Image G-06604 Royal Museum, BC Archives

An illustration of the extent to which just one First Nations group utilized the once prolific salmon resource comes from the report of a fisheries officer in 1904. He reported that the Babine tribe caught

500 to 600 salmon a day in their weir fishery in the Upper Skeena River, and that they had caught 750,000 salmon that year (Harris, 2001). The fishery was clearly abundant.

Prior to colonization, the level of salmon consumption was estimated to be around 400-500kg per capita being consumed by a Stó:lō population in the Fraser basin (Smith D. , 2001). This suggests 4 to 12 million salmon were harvested and consumed annually, not including fish harvested for trade, or for ceremonial purposes (Smith D. , 2001). Other evidence suggests hundreds of tonnes of herring were sustainably harvested annually (Morin & Evan, 2022). It is worth noting this level of harvesting did not constitute overfishing, as the stocks were reliable for thousands of years.

It is also clear that First Nations people possessed the techniques and technologies to catch many more salmon than they actually did (Taylor, 1999). Their restraint illustrates the success of their active management and may also reflect their lower population numbers of around 200,000 prior to 1800. This dropped dramatically to only tens of thousands by 1850 after diseases such as smallpox, measles, mumps, cholera, and gonorrhea were introduced (Lackey, Lach, & Duncan, 2006).

The First Nations peoples developed a range of preservation techniques including drying in air on rack and smoking. This helped them store and distribute considerable volumes of the fish to consume during the rest of the year when the seasonal salmon runs were not occurring.

Figure 4: First Nations preservation of salmon to allow year-round nutrition Source: https://searcharchives.ucalgary.ca/index.php/a-e-pickford-fondshttps://searcharchives.ucalgary.ca/index.php/a-e-pickford-fonds

With First Nations groups throughout the catchment, allocation and sharing of the seasonal salmon resource became embedded within systems of rank and privilege. Wide networks of ceremonial redistribution, trade, and governance processes for recognizing and transferring fishing rights to fishing areas were established at cultural gatherings. These celebratory cultural festivals of music, singing, dancing, storytelling, and games of tribes are referred to as *potlatches*. Families and often neighboring tribes came together for such events. A ceremonial demonstration of one's wealth was undertaken, through giving away or destroying wealth or valuable items[2].

'*It is the great desire of every chief and even of every man to collect a large amount of property, and then to give a great potlatch, a feast in which all is distributed among his friends, and, if possible, among the neighboring tribes.*' (Boas, 1888)

[2] https://indigenousfoundations.arts.ubc.ca/aboriginal_fisheries_in_british_columbia/

Potlatch goods were prepared by a house group from its territory's resources, so served as a proxy for the repeated assessment of the sustainability of their fishery management. Status was gained not by accumulating wealth, but rather by giving it away. Titles were discussed negotiated and affirmed at such events which gave rights to fishing territories and access points (Clutesi, 1969) (Davidson, 2018) (Swanton, 1905).

In 1888, the American anthropologist Franz Boas, described the potlatch as a mechanism that hinders single families from accumulating wealth.

'*Every present received at a potlatch has to be returned at another potlatch, and a man who would not give his feast in due time would be considered as not paying his debts*.' (Boas, 1888)

If the flow of wealth in from the territory of a group declined, then the rank of their chief also declined. As rank and status were aligned with distributing, rather than accumulating wealth, there was little danger of titleholders hoarding resources for their individual benefit (Weinstein, 2000).

The importance of subsistence hunting and gathering traditions to the First Nations has not diminished over time. First Nations peoples continue to hunt and gather in the Fraser River Basin today. Historical pressures, such as the onset of the fur trade, colonial settlement, and modest reserve lands, forced First Nations to compete for food with colonial European settlers and in some cases other groups of First Nations.

Today, First Nations must also contend with habitat and species loss as well as hunting and fishing regulations that have impacted their ability to practice subsistence and cultural traditions on the land and water (The Fraser Basin Council, 2013). Salmon was particularly important for food but also maintained social and ceremonial significance for the culture of First nations people[3] bringing wealth and trade.

First Nations people have led multiple environmental legal actions against the Government and industries which they argued were impacting the wild salmon through mismanagement. In addition, First Nations have come to play key roles in several conservation groups and contribute to research.

Past Director of the Fraser Basin Council, George Saddleman, offered this insight to the current circumstances of the Fraser River:

"*Our indigenous knowledge shows us how we must respect Mother Earth. This knowledge provides us with cultural principles for our future generations to embrace and make things right*." (The Fraser Basin Council, 2013)

Nlaka'pamux Elder described the First Nations philosophy as follows:

"*In our language there are no words for 'environment' because we have always been taught that this is part of our everyday living. Our everyday teachings from our parents, grandparents and great-grandparents show us how to look after the foods that we depend on and that are part of the environment, and that's also part of spirituality*". (The Fraser Basin Council, 2013)

Colonial impacts on the Fraser River

The arrival of colonists in British Columbia heralded a shift in the politico-cultural dynamic. The new arrivals quickly sought to impose their authority over nature and exploit the natural forestry, mining, fisheries, and water resources to accumulate wealth and grow the economy.

[3] https://indigenousfoundations.arts.ubc.ca/aboriginal_fisheries_in_british_columbia/

The shift in value systems was made more apparent when the colonial Government issued a proclamation in 1883 which made engaging in, or assisting, a First Nation's potlatch festival an illegal misdemeanor punishable by imprisonment. Missionaries and government agents considered it "a worse than useless custom" that was seen as wasteful, anti-Christian, unproductive, and contrary to 'civilized values' of accumulation (Cole & Chaikin, 1990).

Placing short-term economic gain above the protection of ecosystem function appears to be a foundational force through time in collapsing the salmon and other fish populations.

Fur trade

After earlier Russian fur traders explored to the north of the Fraser River, the Spanish began to establish outposts, before the arrival of the British to settle with the Spanish after 1774. Sea otter and beaver hunting, primarily for the European fur trade, took place along coastal British Columbia. The furs were sought to make felted hats and luxury clothing for the fashion industry of the day. The Hudson Bay Company established a fur trading outpost at Fort Langley in 1820s. First Nations traded salmon with the fur traders at Fort Langley in 1827[4]. The hunting and processing skills of First Nations people were commonly used to acquire the fur skins, which were then traded for valued items to the European fur traders who took the fur back to Europe for the fashion industry[5]. When the Hudson Bay Company established Fort Victoria in 1842 colonial arrivals began to arrive in numbers by boat.

The hunting of beavers in some cases resulted in their beaver dams falling into disrepair and breaking down, thereby altering river hydrology, and resulting in the loss of salmon habitat for juvenile rearing in freshwater (Bouwes, et al., 2016). The potent economic driver of personal wealth accrual and growing rates of consumption in Europe and America, fed into over-exploitation of beavers by the fur traders contributing to some of the first forces of decline of salmonids in the Fraser River and other catchments of coastal British Columbia.

Mining

In early 1850's the First Nations *Nlaka'pamux* people discovered gold in the river bars of the Fraser River triggering a gold rush to Yale. By 1858 nearly 20,000 people had arrived via boat from San Francisco to seek the riches. This is touted as the catalyst for colonial settlement. It triggered river travel to the uppermost navigable town of Yale. When gold deposits at Yale dwindled miners pushed north into the Cariboo region making new gold strikes at Quesnel Forks, Keithley, Williams and Antler Creeks. The demands created by thousands of miners led to the British Government construction of the 530 km long Cariboo Trail for wagon freight to connect the communities to the coast (Mulvihill, Morrison, & MacIntyre, 2005).

Any concerns about abatement of industrial pollution from mine tailings were viewed as unnecessary costs that could impede these important economic resource extraction endeavors. Hence the rivers, lakes and estuary were narrowly viewed as offering important waste disposal services for the development of industry. The resource dependent communities that sprung up around the mining sites tolerated the pollution, as did provincial Government in its push for economic development (Keeling A. , 2004).

Earliest techniques involved hand mining stream bed alluvial sediment deposits, known as placer mining, with the gold separated through use of a sluice box. These deposits are most often near existing streams and water is often used in the mining operations to separate the minerals from the

[4] http://tidestotins.ca/timeline/
[5] https://greatbearrainforesttrust.org/wp-content/uploads/2018/08/5-Fur-Trade-Era-1770-1849.pdf

gravel. The water and mobilized sediments were returned to the stream, contributing to increased turbidity and smothering of benthic habitats.

Placer mining was only feasible in rich gold deposits. As these declined, the practice diminished and was replaced by larger scale more capital intensive and more polluting methods capable of exploiting lower grades of material. Around the 1880's hydraulic mining techniques were introduced. This involved blasting water at the mining site to erode the material so the gold could be filtered out (Figure 5). Inherently this mobilized considerable sediment loads and released heavy metals that damaged salmon habitat in the receiving salmon lakes and waterways.

Figure 5: Hydraulic mining Source: Quesnel & District Museum http://www.quesnelexhibits.ca/images/mining/picture4.jpg

The extent of earliest impact on salmon stocks was not able to be quantified at that time due to a lack of catch data and monitoring. Based on the experience of other pacific salmon rivers in the USA where gold mining also developed, significant declines in abundance were driven by early mining activity (Yoshiyama, Fisher, & Moyle, 1998).

BREAKOUT BOX **

The historical operation of the Bullion Pit was the largest hydraulic mine used vast volumes of water, requiring 155 square kilometers of catchment, damming of lakes and construction of 33 miles of hand-dug diversion channels for water to run the operation. Around 20 million liters of water were used in an average year. The mine excavated an area 3km long, 250m wide and 120m deep[6]. This mine became large scale in 1894 and through multiple owners it shifted 200 million tonnes of material before it was largely abandoned in 1942 (Mulvihill, Morrison, & MacIntyre, 2005). Tailings were discharged into the south fork of the Quesnel River, which resulted in it becoming dammed. The

[6] http://rovinghiker.com/points-of-interests/the-bullion-pit-mine/

prevailing practices of the day meant no restoration of the mined area was required when large scale operations ceased.

Figure 6: Bullion pit formed by hydraulic mining. Source: K Sedgwick[7]

CLOSE BREAKOUT BOX

Pollution regulations on mine operations changed with time, as the scale of environmental impacts and the public's political tolerance for such impacts altered. In the early 1900s industrial discharges were virtually unregulated and appeared reliant on the goodwill of a company to comply, rather than stringent enforcement activities. The provinces competing regulatory aims to support industrial economic expansion While affording environmental protection shaped policy and the vigor (or lack thereof) of implementation.

Fish kills along an entire stream were reported in association with cyanide use in gold mining operations in 1912. The resulting inspection by provincial Assistant Fisheries Inspector A.P. Halliday claimed to have found little evidence of cyanide from the mine's mill operation and added that there was a need to protect the valuable mining operations for it was the economic reason for the associated small towns to exist. His manager had done other investigations that highlighted the mine's role in the fish kill and rejected Halliday's unbalanced report. He then called upon the federal Fisheries department to act. No action was taken to put any costs on miners, leading to decades of subsequent pollution from the mining operations (Keeling A. , 2004).

The often-remote location of mines and their position as often the sole local employer, aligned with Government management which was reluctant to impact their economic activity by demanding control of their pollution, due to a lack of political will before the mid-1960's.

In the years prior to the Second World War gold mining declined. However, mining for copper, zinc and silver increased substantially and required the development of crushing and milling of ore. The scale of mines expanded as methodologies for open cut mines were able to move vast amounts of

[7] https://search.nbca.unbc.ca/index.php/bullion-pit

material and smelters improve extraction of target minerals. This expanded scale also increased pollution. As the industry was adept at using its power and influence to stop efforts to regulate its environmental impacts, by pointing to its economic benefits, there was little to no pollution control on activities prior to the Second World War (Smith D. , 1987). By 1968 open pit mining operations accounted for 40% of mining activity in British Columbia yet no regulations existed to control such activity (Hertzberg, 1983).

In the post war period, the public recreational use of parks increased exponentially with hunting and fishing pursuits reframing society's values around environmental quality and pollution. The sportsmen's' clubs (recreational fishers) began to advocate for ecological and environmental issues that impacted the fishery in the late 1940s and 1950s. In 1957 the province created the Department of Recreation and Conservation, with the Fish and Game branch given the role of reviewing applications for water use which drew them into pollution control activities.

On some occasions the Game Commission were driven to pursue prosecution against mines for failing to comply to controlling tailings pollution to avoid breaches of the *Fisheries Act.* The behavior of mine operators was described variously as 'uncooperative, blunt refusal, defiant, willfully disregarding and hostile to fisheries inspectors attempting to avert mine pollution' (Keeling A. , 2004). A ruling in a 1958 case went against the Fish and Game Branch and set a new, and higher, standard of evidentiary proof to gain a conviction against a polluting mine. The difficulty of obtaining proof of harm to fish, diminished prosecution under the *Fisheries Act* until the 1960s.

The advocacy of sportsfishers and Fisheries government officials were significant drivers of pollution regulatory reforms in the late 1960s. The perceived bias of the provincial Pollution Control Board, who issued permits for discharges, was highlighted by the case of Western Mines who were seeking a permit to discharge tailings and sewage from the mining camp into Buttle Lake. Buttle Lake's waters on Vancouver Island flowed into the Strait of Georgia to the west and north of Vancouver and was another important piece of salmon habitat. The 100 objection letters received during the permit-review process were rejected without comment and permits granted without a public hearing enraging the opponents and triggering the emergence of more organized environmental protest, thereby politicizing pollution as an issue. Subsequently the local municipality took the Pollution Control Board to court who ruled in 1967 'natural justice' had been violated by the Board.

Even after this, later in 1967 the mine began operation with permitted discharge of tailings into the lake, with the compromise negotiated that an independent consultant should study the effects of the tailings. In 1969 the engineer (not a biologist) G.B. Langford declared the impact on aquatic life would be minimal. However, the obvious turbidity plumes continued to alarm regional fisheries biologists within the Fish and Wildlife Branch who said "*how much of this are we to allow under public pressure and for how long?.... What we say and do will affect our credibility as a serious defender of our resource*."

Water monitoring data of metals and water chemistry were collected mostly by the Waste Management Branch of the British Columbia Ministry of Environment. However, little information was collected on the biological effects until 1980 (Roch, et al., 1985).

In 1981 scientists from University of Victoria, sampled rainbow trout from above and below the contamination area and revealed liver copper levels more than 1000 percent above normal, and cadmium 485% higher than normal (Roch, McCarter, Matheson, Clark, & Olafson, 1982). Levels of zinc, copper, lead and cadmium were all above the Environment Canada Guidelines for surface water quality in the receiving water body from the mine's drainage (Austin & Deniseger, 1985).

Fishers had noticed the decline in fish after the opening of the mine. The water tests did not however reveal acute toxicity to tested trout, rather the biggest impacts were occurring at the bottom of the food web. The primary plankton and zooplankton productivity of the lake was depressed, with both abundance and diversity reduced. By 1984, plankton had been reduced to a virtual monoculture and zooplankton were scarce, even though the mine had sought to better treat mine acid drainage and tailings (Deniseger, Erickson, Austin, Roch, & Clark, 1990). Water quality data continued to be collected through to 1986 by (Deniseger, Erickson, Austin, Roch, & Clark, 1990) which revealed that the mine was in almost continuous breach of its Canada's water quality guidelines particularly at depth in Lake Buttle in winter.

In short, the regulation failed to protect the fishery from impacts. This occurred within a declared wilderness park, as near boundless deference was given to support industrial development by the provincial government.

A slow recovery of aquatic life was observed from 1984-1986 as metal levels declined albeit not returning the prior levels of fishery abundance and biodiversity.(Deniseger, Erickson, Austin, Roch, & Clark, 1990).

The incident led to the creation of the Pollution Control Branch, a full-time agency to issue permits, investigate and punish pollution violations. The structural conflicts of interest in being a development supporting agency and seeking to control pollution remained. In 1967, the minister responsible for the Lands, Forests and Water Resources sought to limit objections to applications to only those with a "direct interest" in land, air, or water.

Around 2965 placer mining claims were active at some point between 2000 and 2009 (Nelitz, et al., 2011). It's clear that While there is some regulation now to control discharge of water from these operations, they collectively have the potential to pose some risk to salmon habitat in terms of driving increased sedimentation (Smith O. , 1940) and mobilization of metals.

Gravel mining of alluvial deposits to source material for concrete manufacture creates similar risks to placer and hydraulic mining for salmon habitat through releasing sediment into the river. Around 450 sites were reported to be active in 2000 (Nelitz, et al., 2011).

There are around 12 significant mines extracting industrial minerals (limestone, granite, slate, flagstone, aggregate, pumice, zeolite, bentonite, gypsum, volcanic ash, silica, kaolinite, shale, clay, pozzolan), 5 metal mines (copper, gold, silver, zinc, molybdenum, tungsten, bismuth, magnetite, iron, lead) and 20 major exploration projects. These include both recovery of minerals from eroded gravel/sand and mining primary ore bodies (MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011)(Nelitz, et al., 2011).

Other mining activities in the Fraser catchment include coal port facilities. These can contribute contaminants to the river through flow from tailings dams, open pits, camp facilities, sewage treatment facilities, waste rock piles, roads and storage yards, airstrips, quarries (MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011) and modify streamflow through mining activities altering hydrology of groundwater.

There are also many inactive mines which pose ongoing risks to river water quality due to acid and heavy metal discharge from tailings ponds and operations.

Howe Sound, immediately to the north of the Fraser River, was the site of one of the largest sources of metal contamination of water in North America from the Britannia Mine. The mine covered an area 36.5km^2 with tunnels and open-cut operations. During its operation from 1898 to 1974, there was daily discharge of acid drainage effluent into Howe Sound ranging from four to forty million litres. The effluent contained elevated levels of copper, zinc, aluminium, iron, and manganese. The contamination flows continued into the 1990's with levels of copper in waters near the mouth of Brittannia creek 20 times over the British Columbia Water Quality Guideline causing detrimental effects to salmon fry, mussels, algae, and invertebrates in Howe Sound. Some remediation has occurred since 2001, but ongoing contamination from groundwater continues (Alava, Lukyanova, Ross, & Shim, 2020).

The Mount Polley copper and gold mine experienced a major tailings dam failure in 2014, which resulted in contamination of Polley Lake, flowing down into Quesnel Lake and the Fraser River[8]. The mine was established in 1997 after the forestry industry declined in the 1980s. An estimated 24 million cubic meters of mine waste entered the Fraser River basin including cobalt, nickel, antimony, arsenic, lead, selenium, mercury, and cadmium, all of which can have deleterious effects on fish health and reproduction (Petticrew, et al., 2015). The mine has continued operating and was granted approval to release treated tailings into Quesnel Lake, however on at least three occasions the company has been out of compliance[9].

Substantial local impacts were reported, and longer-term impacts on salmon which typically spawned in this area are anticipated as contamination of critical spawning and rearing habitat has continued to have elevated turbidity and levels of copper impacting on the productivity of the habitat (Hamilton, et al., 2020)[10].

An Auditor General report in 2016 (Bellringer, 2016) recommended that compliance and enforcement be undertaken by a separate entity to the Energy and Mines Ministry as it clearly had a conflict of interest as it was a vigorous promoter of mining. She found insufficient resources, infrequent inspections, and a lack of enforcement to be major risks for repeat events like the Mount Polley tailings dam spill impacting water quality and salmon, thereby driving up risks for the environment.

In 2021 a British Columbia provincial Government audit[11] of code requirements for tailings storage facilities was produced to guide safety. Unfortunately, an audit of existing tailings storage facilities found one in four to be non-compliant. This is all the more remarkable after the Mount Polley mine disaster. A report has identified that the new audit and provincial legislation is still not up to international safety standards, as it fails to consider climate change and extreme weather events (Enerman, 2021). Other weaknesses in the legislation are the absence of compulsory bonds to ensure adequate finance is available to respond to unforeseen disasters and site remediation after cessation of mining[12].

Mining remains an activity which is supported and promoted by provincial Government in British Columbia and Canadian federal Government for its economic benefits[13]. In 2017, British Columbia mining activities were reported to generate more than $11.7 billion in gross mining revenues

[8] https://www.nbcnews.com/science/environment/huge-toxic-dam-burst-canada-could-threaten-millions-salmon-n176246
[9] https://thenarwhal.ca/year-four-tracing-mount-polleys-toxic-legacy/
[10] https://www.cbc.ca/news/canada/british-columbia/mount-polley-2020-study-1.5685631
[11] https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/mineral-exploration-mining/documents/mine-audits-and-effectiveness-unit/audit_of_code_requirements_for_tailings_storage_facilities_final_2021_04.pdf
[12] https://thenarwhal.ca/bc-mining-tailings-ponds-safety/
[13] https://www.investcanada.ca/industries/mining

throughout the province[14].In January 2023 eight new mines or mine extensions, worth C$6.6 billion in investment were in a queue awaiting approval to operate according to British Columbia Premier David Eby[15] .

Oil and gas mining

Oil and gas exploration and development have not been prominent in the Fraser River catchment. In 1904 a gas well near Steveston near the mouth of the Fraser River was used to light the streets. In 1936-1949 two farm gas wells were used for heating and cooking at Steveston in the Fraser River delta (Janicki, 2008). However, major reserves were not identified in the area. Several oil refineries were developed in the Vancouver area 5-10km north of the lower reaches of the Fraser River, with only one now remaining in operation.

Hydroelectric power

Hydroelectric power development on the Fraser River began in the early 1900s but it was limited to tributaries, rather than the mainstem of the Fraser River. Issues with entrainment of salmon smolts in the channels feeding the hydro plants were associated with increased salmon mortalities (Nelitz, et al., 2011).

The large Kemano power project has diverted up to 80% of the flow of the Nechako River since 1952, to the hydro plant, to generate power for an aluminum smelter at Kitimat, in a catchment to the north of the Fraser River. The lowered flows risked exposing salmon to high temperatures so a management plan for water releases is in place to try and limit maximum water temperatures to 20^{o}C. Exposure of migrating adult salmon to elevated temperatures contributes to elevated stress and increased disease. The result is fewer salmon reach the spawning grounds and of those that do, higher numbers suffer pre-spawning mortality. The warming influence of climate change is compounding these catchment modification effects of hydroelectric power generation.

Small scale hydro plants are also present in the Fraser catchment and can pose risks to salmon through their potential to generate supersaturated water which can contribute to gas bubble disease in the fish and the potential to elevate water temperatures by diverting water into their reservoir especially in low flows during summer. However, their effect on salmon overall is considered not significant by researchers testifying at the Cohen Commission (Nelitz, et al., 2011). Engineers built artificial spawning channels in some areas to try and offset the difficulties the hydro plants had made to safe fish migratory passage.

Forestry

Timber mills opened on the shores of the Fraser River in the late 1880’s to process the timber and facilitate the expanding exploitation of the vast forests in the catchment for economic development by colonial interests. Initially the timber which was along the lower river valleys into the uplands was exploited as it could be readily floated to the mills alongside the Fraser River. As well as the catchment water quality impacts which indirectly impacted fisheries, timber mills directly impacted on the fishery through utilizing herring oil for lubricating skid rows which was manufactured locally from herring captured using dynamite blasting in Burrard Inlet. Dramatic declines in herring within Burrard Inlet ensued as early as 1885 (Morin & Evan, 2022).

[14] https://www.mining.bc.ca/economic-impact

[15] https://www.mining.com/eight-new-mines-or-expansions-in-british-columbia-worth-4-9-billion/

The advent of engines to pull massive logs out accelerated the cutting to meet the demand of settlers who were building homes, fencing newly cleared agricultural land and expanding the railway system. Much of the timber in the lower catchment had been removed by the 1930's[16]. With the expansion and improvement of rail and road, timber resources further inland up the Fraser catchment were harvested. There are still significant scale active forestry operations today in the catchment.

The North Arm of the Fraser River branches off as it reaches its delta. From the 1920's the banks of this arm became lined with wood products manufacturers, chemical plants, industrial estates, fish canneries and shipping facilities. In the early 1950's the North Arm was recognized to be suffering lowered dissolved oxygen levels and high bacterial counts due to contamination by various sources of industrial and municipal effluent (Keeling A. , 2004). While the Pollution Board and Public health engineers clearly highlighted the problem at the time, there was no robust pollution-control policy recommendations made, and the pollution committee was disbanded in 1954.

While the provincial policies for forestry were framed around a conservation rhetoric, they promoted the expansion of harvesting and corporatized control of forested land. In 1937 the provincial Government Chief Forester, E.C. Manning, recognized that the legislature of the time which governed timber sales forces "*the licensee or operator into a position where he has no personal interest whatever other than to remove from the land as quickly as possible all existing values*."

Subsequent Royal Commissions in the 1940s and 1950s intended to ensure forests were exploited on a 'sustained-yield' basis created a symbolic image that forests were being protected and conserved to now deliver a perpetual flow of timber and wealth. However, this appears to have done more to shield the private companies involved in the forest industry from public scrutiny, as the old growth stands of public forests were effectively liquidated, with Government oversight, through over-harvesting. This was combined with under investment in restoration and reforestation through to the 1970s (Marchak, 1983) (Wilson, 1987). Most of the State's forest wealth was transferred into the private hands of a relative few, rather than dispersed to the public.

While policy changes in the 1970s and 1980s promoted better forest stewardship through the *Forest Act,* the Ministry of Forests acknowledged in 1984 that the goals for greater restocking of forest land were not being met (Wilson J. , 1987). Private companies, professional foresters and major newspapers placed blame on inadequate Government spending, not applying the same focus to the responsibility of private companies who had profited from the over-harvesting.

Log booms to this day cover large areas of the Lower Fraser River (Figure 7). In 2011 Port Metro estimated that 48 different tenants across 256 log storage leases and permits cover 862 hectares of the Fraser River estuary, with forestry now extending well into the interior of the Fraser basin.

[16] https://www.surreyhistory.ca/nsmills.html

Figure 7: Logs rafting in Lower Fraser River along the jetty, with its newly restored access point for salmon entry Source: Raincoast Conservation Foundation[17]

In addition to loss of catchment shading leading to thermal pollution and loss of insect habitat, forestry activities also create further diffuse source aquatic pollution summarized in table below (MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011):

Pollutant type	Details
Pesticide	glyphosate, triclopyr, picloram and 2,4,-dichlorophenoxyacetic acid (2,4-D), fenitrothion, carbaryl, monosodium methanearsonate (MSMA)
Synthetic fertiliser	ammonia, nitrite, nitrate, phosphate including sewage biosolids products
Sediment	From destabilised forest floor and road construction
Surfactants	amphoteric fluoro surfactants, non-ionic fluoro surfactants, anionic hydrocarbon surfactants
Fire retardants and associated chemicals	diammonium sulphate, diammonium phosphate, ammonium sulphate, ammonium phosphate, ammonium polyphosphate, sodium ferrocyanide

The BC Timber Sales, Government Agency releases plans such as the George Fort in 2017[18], and South Coast Plan[19] as five-year plans that would see much of the forestry land under its control sprayed with

[17] https://www.raincoast.org/connectivity/

[18] https://www.for.gov.bc.ca/ftp/tpg/external/!publish/PMP's/Mackenzie/BC%20Timber%20Sales%20Pest%20Management%20Plan%20MK%202019-2024%20DRAFT.pdf

[19] https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/invasive-species/pest-management/pmp_south_coastal_mainland_21-26.pdf

herbicides including 2,4D, glyphosate and picloram as part of a proposed pest management plan to promote production of the desired tree crop, whilst simultaneously proposing to align with the provincial *Integrated Pest Management Act*.

The forestry industry in the Fraser River is reported to utilize a processed biosolid product, 'Nutrifor', from major sewage plants, as a fertilizer (Cohen B. , 2011). Such use on upland areas risks introducing higher levels of many residual contaminants that are expected to persist in processed biosolids including metals, PFAS, PBDE, pharmaceuticals and dioxins into freshwater habitats that could impact sensitive life stages of developing salmon. Movement of contaminants from sites of soil application into ground and surface water run-off has been demonstrated (Gottschall, et al., 2010).

The timber industry also creates significant point source pollutant streams via the 10 pulp and paper mills, 99 sawmills, plywood mills, 15 wood preservation facilities and other wood product facilities which were all still in operation in the Fraser River catchment in 2011 (O'Neal & Woody, 2011). These are discussed in more detail below.

Forestry and climate change impacts

The warming climate over the last three decades has led to the spread of the mountain pine beetle which has decimated huge areas of forest in the headwater catchments of the Fraser River. Usually, cold winters kill the beetle larvae reducing their numbers. The beetle's spread has now impacted 60%, or 148,821km^2, of the Fraser River catchment.

The loss of canopy has been modelled to increase peak streamflow by 60% (van de Vosse, 2008). The vast dead areas of forest have become the subject of intense salvage logging operations to harvest the timber before it decays in a bid to capture the final economic value. These clear-felled areas increase the amount and speed of run-off, and snowmelt, thereby accelerating soil erosion and increasing water temperature. Models demonstrated that peak streamflow rises to 92% and the frequency of large floods increases from once in 20 years to once in three years after clear felling salvage operations in a pine beetle affected area of forest.

Climate change has also been implicated in the third worst wildfire season on record in 2021 in terms of area burnt, as an extreme heatwave impacted British Columbia. Severe flooding and landslides later in 2021 were likely exacerbated by the prior fire events and clear-fell logging destabilizing slopes and altering run-off[20] (Wood, 2021).

[20] https://sparkgeo.com/blog/wildfires-and-flood-damage/

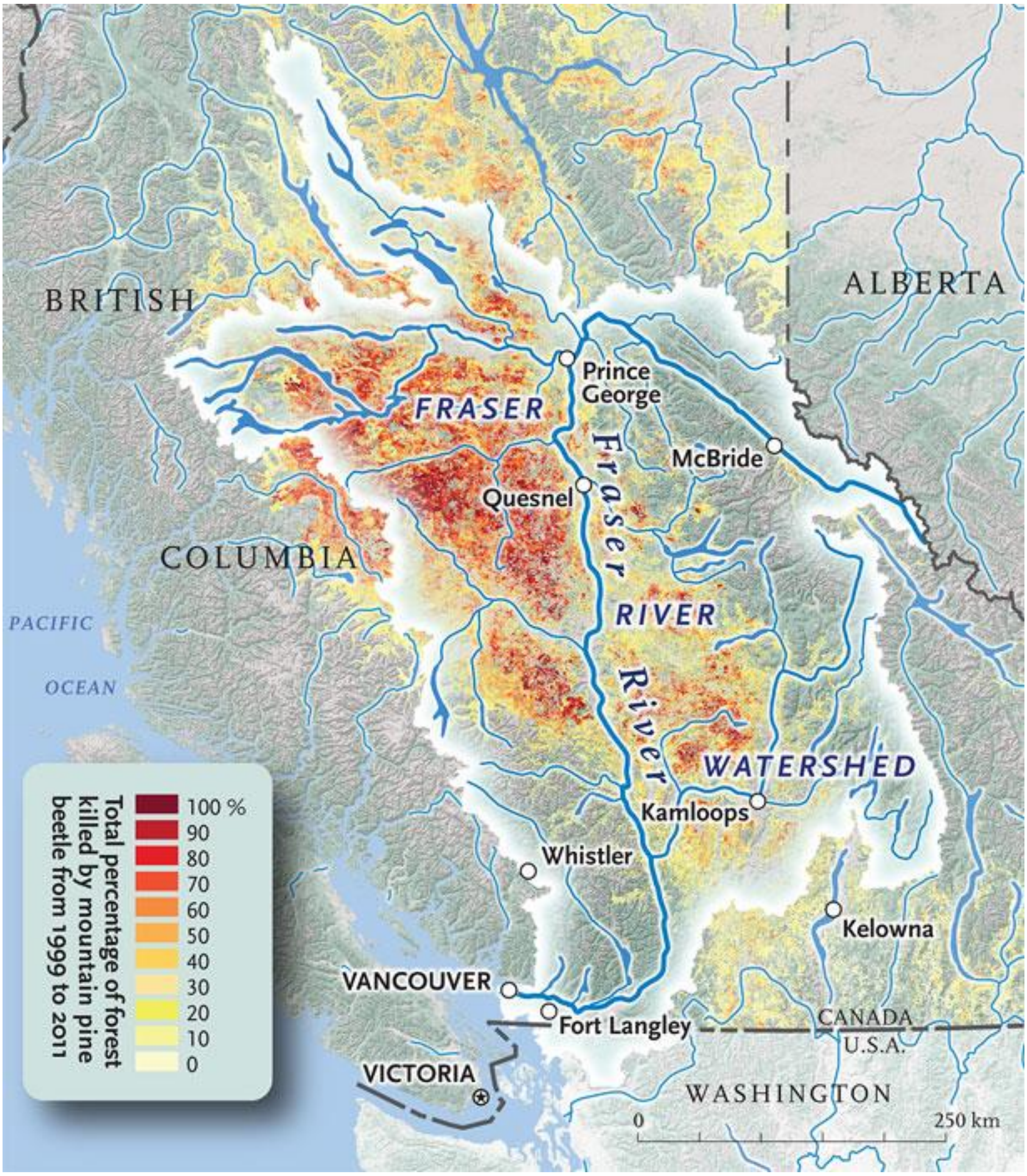

Figure 8: Total percentage of forest killed by mountain pine beetle from 1999 to 2011 (Map: Chris Brackley/Canadian Geographic)

Overland flow and concentrated flow energy is mitigated in undisturbed forests by the organic matter and upper soil horizons, which accumulate water and drain slowly, allowing greater infiltration and reducing the detachment and transport of soil particles. If the forest floor is not removed or heavily disturbed, it effectively protects soil from splash erosion, reduces overland flow velocities, and promotes infiltration of water into the underlying soil. This reduces the magnitude and frequency of the most erosive peak flows, altering the transportation of bed and bank sediments (Orndorff, 2017).

The removal of trees and later construction of roads increased sediment movement into waterways impacting the habitat of salmon through covering gravel spawning areas with sediment, destabilizing riverbanks and removing shade from the rivers resulting in higher water temperatures both in the areas where shading of the river was reduced and downstream (Roon, Dunham, & Groom, 2021) (Dugdale, Malcolm, Kantola, & Hannah, 2018). The many culverts, flood control structures and crossings created new barriers to salmon movement destroying the connectivity of habitat on the lower Fraser River and floodplains. Around 85% of the habitat which was present in 1850 is now recognized to have been lost due to human impacts on the lower Fraser River (Finn, et al., 2021). This amounts to around 1700km of stream length that has been completely lost.

Forestry and Pulp mills

The rise in demand for paper, particularly for the booming US newsprint and packaging market, saw a dramatic expansion in pulp mills in British Columbia funded by British and US capital. The abundant soft wood timber resources and access to plentiful water saw pulp mills established in the early 1900's at sites that drain into the migration pathways of Fraser River salmon, such as Swanson Bay, Port Mellon, Woodfibre, Powell River and Ocean Falls. From the earliest times the utilitarian attitude of the pulp industry to waste disposal was parallel to that of the sewage and mining industry with consequences for the receiving aquatic environment.

In the early 1900's the process of pulp manufacture used around 364,000L of water per tonne of pulp product produced, to separate wood fibers. The process inherently created significant volumes of wastewater which contained soluble and insoluble wood fibers, lignin, residual process chemicals and chemical condensates as well as creating noxious odors and consuming significant amounts of power. By the 1950s even with some efficiency gains sulphite mills still generated around 227 million litres of wastewater discharge per day (Keeling A. , 2004). The high load of organic material in wastewater created very high loads of Biological Oxygen Demand (BOD)- a 500 ton per day sulphite mill emitted equivalent BOD to a sewage wastewater plant servicing a city of 2 million people (Waldichuk, 1962). The impact of such waste on aquatic ecosystems depends greatly on the ability of the receiving water to dilute and disperse the waste. Where mills have poor flushing around outfalls, smothering of the seafloor and creation of low oxygen zones at depth were reported (Waldichuk, 1962).

More mill construction took place adjacent to Fraser River salmon migratory waters at Harmac after 1945 with more industry expansion to Elk Falls and Crofton in the mid-late 1950's.

Through the 1940s to 1960s provincial authorities appeared disinclined to pursue the mills to control their pollution, and as the mills were often the sole employer in the town that sprung up around them in a remote area, the local community were often not vocal in expressing concerns about mill pollution (Keeling A. , 2004).

In the absence of strong provincial pulp mill wastewater regulation in the period up to the 1960s, the federal *Fisheries Act* offered the greatest opportunity to regulate the pollution. Where damage to fish could be easily demonstrated, such as fish kills, the Act could be more readily exercised. The *Fisheries Act* was first enacted in 1868 as a building block of Confederation. Even though the *Fisheries Act* contained provisions that specified that no deleterious substance may be deposited into fish-bearing waters this did not mean that enforcement and compliance were undertaken by the department. The scene was set by the Fisheries Minister in 1937 when he stated that he "*seeks to place no unnecessary impediment to development of any industry*" (Keeling A. , 2004).

The default of the federal department became performing research and negotiation, rather than strict enforcement of the *Fisheries Act.* Nonetheless it is clear that improvements in pollution controls were strongly motivated by fisheries interests in the community, such as sportsmen groups and the federal government, due to the presence of the historically abundant and valuable salmon fishery of the Fraser River.

Groups like British Columbia Wildlife Federation were prominent in shaping public opinion through media and liaison with Government on pollution control asserting in 1968 that "*prosperity that depends on the fouling of our environment can only give us short-term benefit. It can hardly pass for 'progress'*." Yet these industries and the prosperity they create, continue to be promoted as the definition of modern 'progress'. The false premise of industrial 'progress' is yet to substantially redirect the politico-social actions of the country.

Even after penalties were increased in the *Fisheries Act* in 1961, the lack of political will and scientific certainty of the impacts of mill pollution meant it continued to go on without enforcement.

The International Pacific Salmon Fisheries Commission (IPSFC), federal Department of Fisheries and the provincial Fish and Game Branch formed a committee in 1963 to estimate impact of pulp mill effluent on fish. They were the first to reject the paradigm of environmental assimilation as a means of waste management. Instead, they endorsed the principle that "all wastes from industrial plants should be treated by any known methods to reduce their toxicity to a minimum regardless of the degree of subsequent dilution available in the adjacent waterway." (International Pacific Salmon Fisheries Commission, 1964).

By the mid-1960s a bioassay was being used to interpret toxicity of mill effluent, exposing yearling salmon to various concentrations for durations up to 4 days and assessing the mortality. This allowed the calculation of an LC-50 (lethal concentration at which 50% of the test fish died). Pollution officials applied an arbitrary safety factor to this value, to conclude that 10% of this LC-50 value, when present in the environment, would be safe. This methodology systematically overlooked chronic long-term toxicity and sub-lethal effects that could occur at lower concentrations.

The shortcomings of the acute toxicity test were revealed when the International Pacific Salmon Fisheries Commission supported research in 1963 that examined effects on spawning fish, eggs, alevins (larval salmon still carrying a yolk sac) that identified adverse outcomes at exposures as low as 2 per cent of the effluent.

The development of the kraft process for pulp production in 1948 allowed the utilization of sawmill wastes. This first triggered further expansion of the industry on Vancouver Island at Port Alberni. Subsequently, from 1964-1970, multiple kraft pulp mills were established on the Fraser River catchment at Prince George, Kamloops, and Quesnel to process sawmill waste[21] from the extensive forestry activities in the catchment. Prince George's pulp and bleach effluent alone was estimated to generate 100 million litres of effluent per day (Keeling A. , 2004). By 1966 there were 7 inland pulp mills in operation. The volume of pulp production in B.C. grew from 2 million tonnes in 1960 to 5.27 million tonnes in 1975 as the Government offered favorable licensing schemes to access forests and promote industrial expansion.

The federal Department of Fisheries and the IPSFC were pivotal in convincing the inland pulp mills at Kamloops and Prince George to install retention basins for partial biological treatment of the mill effluent and created monitoring plans intended to ensure their effluent was considered non-toxic at the point of release into the river.

[21] https://www.pulpandpapercanada.com/looking-west-historical-overview-of-the-industry-in-bc-1000141957/

However, some mills frequently failed these tests which were embedded within the provincial permits from the Pollution Board. Enforcement by the Government was lacking, as their deference to the short-term economic priorities over environmental protection prevailed (Keeling A. , 2004).

The proxy measurement for the effectiveness of pollution control measures was the survival of commercial fish species, leading to geographic differences in how much pollution was considered tolerable. The pollution generated by these mills into the Fraser River quickly became a flashpoint for environmentalists and fishers concerned about its impact on the fishery in the late 1960s and early 1970s. Nutrient build-up in the Thompson River and Kamloops Lake in the early 1970s necessitated further mill upgrades.

The identification and classification of new types of pollutants such as persistent organic pollutants like dioxins and heavy metals eventually contributed to changing regulation of the polluting discharges. The process of what has been termed 'molecular bureaucracy' attempted to ease the load for regulators by applying a number to classify the molecular identity of each chemical. Thereafter information about the chemical's toxicity and behavior could be catalogued around it. This oversimplification of chemistry has done equal measures of harm as it failed to recognize many compounds differing forms, had no information on new chemicals prior to their release and offered no information on the impacts of the many interactions between the myriad combinations of chemicals when they ended up in the environment (Hepler-Smith, 2019). This process of 'molecular bureaucracy' did serve the interests of the chemical industry to facilitate and legitimize more and more chemicals into use.

The *Canada Water Act* was created, and the *Fisheries Act* amended in 1970 and the Department of the Environment was created in 1971 thereby extending federal management of water quality. However, the provisions to create planning authorities which were intended to distribute the pollution assimilatory capacity of the river, under the *Canada Water Act* were never established.

In 1971 Department of the Environment created and managed the new Pulp and Paper Effluent Regulations, by creating standards that effluent had to meet in relation to biological oxygen demand (BOD), suspended solids and some toxic constituents, in addition to having 80% of fish surviving a 96-hour bioassay in 65% effluent. Compliance and enforcement remained an issue particularly where the improvements demanded to effluent did not result in production improvements for the mills.

The shift to greater pollution regulation in the 1970s saw more prosecutions of mills for major pollution breaches causing fish kills under the federal *Fisheries Act.* However, the long-term degradation of aquatic environments remained largely beyond prosecution. The geographically remote location of mills meant they frequently argued their economic importance as an employer should be considered before enforcing tighter effluent regulation which would place more economic costs on their operations. The Government's dual roles of promoting economic development and controlling pollution were clearly at odds with each other.

Pulp production techniques utilizing toxic chemicals such as chlor-alkalis and chlorates, and the use of preservative treated wood chips (e.g. Poly-chlorophenols (PCP)) generated highly toxic chemicals (PCBs and dioxins) which were discharged as part of the complex effluents to the aquatic environment (Macdonald, Ikonomou, & Paton, 1998). It was not until the late 1980s that the detection of the persistent dioxins and furans in pulp effluent and their risks as human carcinogens became known. This triggered more policy adjustment in the *Pulp and Paper Mill Regulations* under the federal *Fisheries Act*, coming after years of pollution emissions of highly persistent toxic chemicals had been discharged into aquatic food webs. In 1989 the industry shifted from liquid chlorine to gaseous chlorine when the new regulations became effective. This reduced the release of the by-product dioxins into aquatic environments by some 97% (Hagen, Colodey, Knapp, & Samis, 1997).

The industrial processes have changed over time to improve plant efficiencies with a by-product benefit that new techniques reduced dioxins and furans, however changes led to generation of other toxicants which became better described through the 1980's-1990's in pulp mill effluent (Macdonald, Ikonomou, & Paton, 1998).

The process of chlorine bleaching in pulp mills continued to generate toxic emissions to the Fraser River and waterways in the migratory path of salmon such as chlorophenolics, resin, fatty acids, and some polycyclic aromatic hydrocarbons (PAHs) like retene.

Levels of some pulp mill chemicals in the Fraser River measured in 1994-96 were reported to be lower than reported sub-lethal toxicity thresholds described in 1998 (Szenasy, 1998). However, the potential risks from mixture toxicity and cumulative risks were not assessed.

Within the Cohen Commission of Inquiry into the decline of sockeye salmon identified 12 categories of substances from pulp mills of toxicological concern including: ammonia, chlorides, mercury, benzene, toluene and chlorophenols (Cohen B. , 2012).

Today, more sensitive assays are available to explore different health endpoints such as endocrine and immunotoxic effects, however these are yet to be deployed as regulatory tools to control industrial pollutant impacts on aquatic ecosystems.

Sawmills, plywood mills and particle board mills

Numerous timber businesses operate within the Fraser River basin. Within the Cohen Commission of Inquiry into the decline of sockeye salmon identified 9 categories of substances of greatest concern from these operations including: ammonia, phosphorus, sulfides, sulfates, and formaldehyde (Cohen B. , 2012).

Wood preservation facilities

At the time of the Cohen Commission Inquiry into the decline of sockeye salmon in 2011 there were at least 15 wood preservation facilities operating within the Fraser River basin. While earlier use of the wood preservative pentachlorophenol had been removed, high priority chemicals such as creosote and chromated copper arsenate remained (Cohen B. , 2012). There are large quantities of wood preservatives used in the Fraser Basin- more than 3.2 million kg in 2003, of which more than 2.1 million kg was creosote. In 2003, more than 200,000kg of anti-sapstain chemicals were used. The most common products were dodecyl dimethyl ammonium chlorine (DDAC), disodium octaborate tetrahydrate and iodocarb (IPBC). While management measures limit movement of these chemicals off the sites where they are applied, there remains a risk of leaching from the wood products themselves at the end-use destinations such as docks, pilings, and bridges within the catchment (Ross, et al., 2013).

Exposure to these chemicals is recognized to cause stress, impair osmoregulation, swimming and impair the fishes sense of smell (olfaction) in salmon (Wood, Johnston, Farrell, & Kennedy, 1996) (Johnston, Seubert, & Kennedy, 1998) (Tierney, Taylor, Ross, & Kennedy, 2006). Disturbance of the sense of smell can negatively impact salmon's ability to navigate back to their natal streams.

Agriculture

British Governor Douglas made a proclamation in 1860 which gave each British subject the right to pre-empt a quantity of land up to 160 acres at a rate of ten shillings per acre, provided the land were improved, giving the owner clear title (Ormsby, 1945). Herds of cattle, horses, mules, and sheep were imported from Oregon USA. Some subsistence farming soon began to service settlers needs and support the Gold Rush and its demand for horses, with cattle ranching in the Thompson Valley established. Dairy farming along the lower Fraser River was producing butter for miners by 1868.

The landscape was altered by removal of beaver dams to modify hydrology for agriculture when farming became the dominant industry over fur trading, and flood mitigation was prioritized.

As road and rail access was constructed the cattle industry moved further into adjacent valleys through 1880's and 1890's.

Some early farmers supplemented their income through selling furs, working for logging companies and taking up licences to catch fish from the river. Since that time land clearing progressed often through inviting timber companies into clear land, or through burning and use of pigs[22]. Forestry began at large scale in concert with agriculture in these areas from 1870 until the area was largely deforested by 1930.

By around 1886 Vancouver had grown to a population of 8000. Farmers were delivering dairy, chickens, turkeys, fruit, vegetables, and grains[23]. The Fraser River valley was found to be suitable for specialty crops like hops, which were grown from around 1892. Drainage, dyke installation and irrigation were promoted by a Government Act in 1911. The ploughing of soils progressed initially using livestock and later steam tractors to facilitate cropping on lowlands for fodder production to support a rapidly growing dairy industry. By the time most farms were connected to electricity grid in the 1940's milking herds had increased to more than 100 head.

Landscape modification for agriculture and urban areas resulted in extensive modification of wetlands and lowland streams, through drainage and construction of barriers resulting in losses of access to 1700km of stream length and 85% of salmon habitat in the floodplain areas of the Fraser River (Finn, et al., 2021).

Major flooding in 1948 destroyed crops of hops triggering a shift into corn and hay production[24] before a shift into vegetable production in the late 1950's and early 1960's. By the late 1980's under 10% of land was under fodder production, with emergence of greenhouse-grown product, cranberries, and blueberries[25].

The registration of pesticides in Canada is overseen by the federal *Pest Control Products Act* and is reviewed/managed by Health Canada's Pest Management Regulatory Agency (PMRA) that was created in 1995.

The sale and use of pesticides is regulated provincially under the *Integrated Pest Management Act*[26]. The Act does not appear to offer any explicit regulation to enforce reduction of pesticide use or require users to explore alternatives to pesticide use.

In 2007 the British Columbia Ministry of Environment and Climate Change Strategy promoted a shift to Integrated Pest Management (IPM) and alternatives to pesticides. A manual was produced to assist

[22] https://www.surreyhistory.ca/agriculture.html
[23] https://www.surreyhistory.ca/agriculture.html
[24] https://www.communitystories.ca/v2/knee-high-1st-july_hauteur-genou-1-juillet/story/first-hops-corn/
[25] https://deltafarmland.ca/resources/history-of-farming-in-delta/
[26] https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/03058_01

this[27]. However, perceptions of increased risk to crops by farmers and their historically engrained pesticide dependent habits make voluntarily shifting production strategies very slow.

The success of such programs internationally has been poor, with use of pesticides continuing to expand globally (Deguine, et al., 2021). The problem with ill-defined definitions of IPM is exemplified in the regulation under the *Integrated Pest Management Act*[28] of the sale and use of pesticides where The Act does not appear to offer any explicit regulation to enforce reduction of pesticide use or require users to explore alternatives to pesticide use.

Water extraction and use

From the first British Columbia *Gold Fields Act* in 1859 miners could claim a specific amount of water for their mining operations. In 1865 the Land Act specified that the grant of exclusive water privileges required the construction of a ditch or flume for the conveyance of water and provided for irrigators to claim water. This system replaced the English common-law traditions of riparian rights that protected stream-side landowners rights to flows "undiminished in quality or quantity", thereby recognizing water itself, if not access to it, as a common-property resource (Teclaff, 1985).

In 1892 the province sought to make it clear in the *Water Privileges Act* that the ownership of water was explicitly vested in the Crown and created a licensing system for its use. The Government justified the removal of riparian rights through highlighting the need to promote the maximum beneficial use of all resources, including water (Keeling A. , 2004).

Through measurement of flow rates and water records the governance of water was removed from its ecological framing to become a commodity to fuel capitalist development projects (Scott, 1998). Fragmentation of nature into its component resources for management, renders governance structures unresponsive to the ecological interplay between the differing natural resources. The allocation of water licences to private concerns allowed secure tenure and the appropriation of what was ostensibly public water. That salmon and other fish had water requirements (volumetrically, seasonally and in terms of quality) to successfully signal migration, spawning and feeding were not explicitly acknowledged and thus became externalities to the management of water.

Water quality was not a priority under this scheme. So called "beneficial use" prioritized economic development over the protection of water quality.

There are thousands of water licences for water extraction from the Fraser River catchment and tens of thousands of wells providing potable drinking water, water for irrigation agriculture, fish hatcheries and other industry (Nelitz, et al., 2011). The vast bulk of water use is unmonitored and uncontrolled for agriculture (Hall & Schreier, 1996). In the lower Fraser Valley, there is also significant use by the chemical industry, wood and food processing, paper, and allied industries.

The *Fish Protection Act* prohibits the construction of any bank-to-bank dams in the Fraser River.

Cement and concrete plants

From the early 1900's cement and concrete factories were established in several locations on Vancouver Island discharging effluents to the Strait of Georgia. In the 1950s plants were also

[27] https://www.crownpub.bc.ca/Product/Details/7610821056_S#/?statesave=true
[28] https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/03058_01

constructed on the banks of the lower Fraser River that helped produce the concrete and cement that build much of modern Vancouver and supported development of other industries like oil and gas. The large Ciments LaFarge plant on the Fraser River operated for 40 years prior to modernization in 1999 which improved environmental emissions lowering its sulfur and particulate emissions While doubling the plant's production capacity to over 1 million tonnes per annum. The company have another cement production site further up the Fraser Basin at Kamloops.

The Richmond plant on the banks of the lower Fraser River, has been shifting from coal to alternative fuels such as waste from construction and demolition works, nylon fibers from tire recycling, plastics – especially the portion that cannot be recycled by recyclers (labels and film), carpets and carpet fibers, and saw dust[29]. Such new fuels are likely to generate new toxic emissions risks such as dioxins, furans, PFAS and nanoparticulates. Ultimately through burning waste indirect support is provided for the further extraction of fossil fuels for the generation of more virgin plastic and production of other waste in a linear consumptive economy. The Lafarge Richmond plant is also planning to build a pilot CO2 capture facility that seeks to convert the emissions into formic acid and trial injection into concrete or fly ash[30].

Figure 9: Cement plant on the north arm of the Fraser River 1981 Source: BC Archives Royal BC Museum I-10545

At the time of the Cohen Commission of Inquiry into the decline of sockeye salmon in 2011 there were 17 plants operating in the basin mostly on the lower River. The contaminants of greatest concern were noted to be pH, total suspended solids, sodium, potassium, chlorine, sulphates, oil and grease, and metals such as aluminum, arsenic, copper, chromium, lead and zinc (Cohen B. , 2012). The concrete industry is also a significant emitter of carbon dioxide contributing to climate change effects.

[29] https://www.zkg.de/en/artikel/zkg_Without_ships_nothing_would_run_in_Richmond_2451787.html

[30] https://www.zkg.de/en/artikel/zkg_LafargeHolcim_launches_carbon_capture_project_in_Canada_3435293.html

The demand for sand and gravel for concrete was largely fed from material dredged from the Fraser River which altered the hydrology of the lower Fraser River delta area.

Urbanization

Sewage

Post-colonial arrival there has been considerable urban growth, mostly in the lower Fraser Valley. The major city of Vancouver spread is across 23 jurisdictions- 21 municipalities, one district and one First Nation. Metro Vancouver oversees five major wastewater treatment plants to service the population of around 2.63 million people in 2022. The population growth and associated industry expansion has extended urbanized areas into former agricultural land and led to an expansion of pollution sources. There are 90 sewage treatment plants in the Fraser River valley (Cohen B. , 2012).

Initial planning for sewage was contingent on the concept that the Fraser River and adjacent marine waters had capacity to assimilate the waste. Hence disposal to this location was considered efficient and reliant upon the bio-physical processes in the river. These attempts to construct the Fraser estuary as a sink for wastes failed to account for the complexity and variability leading to long term deterioration of the aquatic environment (Keeling, 2005).

A dominant theme of the hubris of colonial developers to over-estimate their abilities to predict and manage the complexity and variability of nature run through to the present day. The area of waste disposal came to be dominated by engineers who rationalized discharge to the environment as economically efficient exploitation of a resource within a capitalist system (Keeling A. , 2004).

Vancouver was like many North American cities, where initially greater effort was placed on water purification for safe drinking water, rather than develop expensive waste-treatment and disposal technologies.

Starting around 1913 the city of Vancouver began efforts to manage waste through developing large-scale sewerage plans after outbreaks of typhoid and other water-borne communicable diseases spiked in 1910-1911 and were linked to deteriorating water conditions. Inter-municipality rivalry and the high cost of infrastructure impeded efforts which led to sewage impacting local beaches and waterways. Infrastructure developed at this time did not always separate sewage from stormwater and in many cases combined sewers discharged into shallow streams.

An expert panel convened in 1952 to consider pollution policy in British Columbia. It asserted that “pollution is an aspect of proper resource use” and that the ocean “can act as a natural treatment system, [and] should be used for this purpose with respect to sewage” (Keeling A. , 2004). The engineers subsequently defined pollution in terms of levels of dissolved oxygen and numbers of coliform bacteria. Exactly how this would impact on the ocean’s other natural roles of serving as an aquatic ecosystem were not given any paramount importance.

In response the Pollution Control Board was created in 1956 that shifted some management from the local municipality to the provincial scale to come up with workable solutions to domestic and industrial pollution. However, these had less effect in practice on prevention, rather they perpetuated the notion that the river’s waste assimilation capacity was a resource that would be exploited for economic advancement. The board issued permits to pollute, taking an administrative approach to sharing the presumed waste assimilatory capability of the Fraser River, based mostly on measurement of biological oxygen demand and coliform bacterial counts. The oversimplification of nature was borne of a bureaucratic desire to advance economic development, where environmental harm was downplayed as unfortunate collateral damage.

Fisheries interests, including those expressed by the International Pacific Salmon Commission were cast by the Pollution Control Board as narrow, advising some pollution decisions may go against their interests. Economic, technical and political consideration ruled the day (Keeling A. , 2004).

Through to the late 1960's public concerns grew as persistent pollution problems were unresolved.

A 1967 report for the Pollution Control Board noted that no biological monitoring data was available for the river, only the water quality assay information, on which to form an opinion about the impacts, if any, on the fishery. It noted hundreds of industrial and domestic waste outfalls were in the Lower Fraser River. The engineering notion that management through measurement of coliforms and dissolved oxygen could deliver reliable disposal of waste were repeatedly shown to be unreliable, due to a range of unpredictable environmental parameters like changes in rainfall, tides and wind that left local beaches unsuitable for swimming.

The subsequent political conflicts over sewage treatment and disposal into the Fraser River altered the approach to pollution control in the 1970's. Conservation, ecological and biological imperatives conflicted with previously sanitary engineer-driven systems which were based on a paradigm of "beneficial use" and "full utilization" of provincial water resources to assimilate waste disposal (Keeling A. , 2004).

The Pollution Board then released a policy in 1968, to get all new and existing sewage and organic industrial effluents to install primary or secondary water treatment prior to discharge before 1975. Subsequently a provincial policy was made to require all municipalities to treat their sewage prior to disposal.

Recreational sports fishers and commercial fishers were key actors with other environmental groups in promoting changes to management of water pollution after the Second World War into the 1960's and 1970's.

The net effect of all the activism did not to resolve the sewage waste disposal issue, rather it led to the introduction of longer pipes to take the pollution to a 'larger sink' further offshore in the Strait of Georgia. It also had the effect of turning salmon streams into sewage or stormwater drains and turned the rivers and estuary into sewage disposal facilities.

After much acrimony the provincial cabinet agreed to upgrade Annacis Island to secondary treatment and consider the cumulative ecological effects of sewage disposal and toxic chemicals in the Fraser River in 1975 (Keeling A. , 2004). The upgrade got delayed and instead more testing requirements on effluent were introduced including bioassays for toxicity, heavy metals, phenols, oils, and other chemicals. The Annacis plant regularly failed the bioassay tests with acutely toxic effluent even at low concentrations. Even with this, the reviews in 1980 failed to recommend treatment upgrades, instead continued to promote the dilutionary capacity of the river and improving source control.

Fish kills from deoxygenation in July 1980 led to charges being laid under the federal *Fisheries Act* on the Vancouver municipal authorities, at the instigation of the Union of B.C. Indian Chiefs. They pleaded guilty. Offenders were fined $5000 each.

The Annacis Island and Lulu Island plants which discharge into freshwater reaches of the Fraser River were only upgraded to secondary plants in 1998. The large volume Iona Island and Lions gate plants remained primary treatment only as they release their effluent into the marine environment which was deemed to be a less vulnerable environment.

Today, sewage from four major plants, including Iona Island and Lions Gate, that service most of the population remains only secondary treated, even a decade after the Cohen Commission reports highlighted this risk to water quality as a threat to salmon populations and community action groups have advocated for ~70 years for better standards of treatment[31]. A plan is now in place to upgrade the Iona plant to tertiary treatment by 2030[32].

Municipalities in the greater Vancouver area still have some combined sewage and stormwater, resulting in numerous overflows of untreated waste each year when flow rates exceed plant capacity (Cohen B. , 2012).

Other plants, such as Lulu Island, Annacis Island and Northwest Langley discharge secondary treated sewage into the lower Fraser River estuary generating the largest sources of biochemical oxygen demand, suspended solids, ammonia, and total phosphorus pollution (Hall & Schreier, 1996). The British Columbia Ministry of Environment set the limits for compliance of individual sewage plants in relation to biological oxygen demand (BOD), faecal coliforms, turbidity, nitrogen, phosphorus, and total suspended solids (TSS). The frequency of sampling ranges from weekly (highest flow plants) to quarterly (lowest flow plants).

Seven smaller sewage plants in the Lower Fraser Valley generate secondary treated sewage.

Under some circumstances the effluent must pass a 96hr acute toxicity test using rainbow trout as the test organism (*Biological Test method: reference method for Determining Acute Lethality of Effluents to Rainbow Trout* (Reference Method EPS 1/RM/13). Contaminants are not required to be monitored at most plants.

The effluents contain an array of contaminants many of which were highlighted in the Cohen Commission technical report on potential effects of contaminants on Fraser River sockeye salmon (MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011). The contaminants are transported up to around 10km from point of release (Johannessen, Macdonald, Burd, van Roodselaar, & Bertold, 2015) and persistent pollutants may move much further through integration into the aquatic food webs.

Grey water from septic systems, vessel discharge and wastewater in some locations such as Shuswap Lake are contributing to disturbance of natural nutrient levels in this salmon habitat in addition to a range of contaminants such as detergents, personal care products and other chemicals (Cohen B. , 2012).

During the Cohen Commission of Inquiry into the decline of sockeye salmon in the Fraser River evidence was offered that even tertiary sewage treatment may not be sufficient to breakdown some pharmaceutical contaminants prior to discharge (Cohen B. , 2011). The trend of increasing area, duration, and severity of toxic algal blooms in the Strait of Georgia has continued in parallel with these

---

[31] https://www.fraserriverkeeper.ca/how_upgrading_the_iona_island_wastewater_treatment_plan_to_true_tertiary_would_fulfill_a_legacy

[32] http://www.metrovancouver.org/services/liquid-waste/projects-initiatives/iona-island-wwtp-project/Pages/default.aspx

nutrient rich discharges from the growing population of Vancouver, expanded agriculture and aquaculture effluents.

Biosolids captured by sewage plants are classified based on criteria under the *Organic Matter Recycling Regulation*[33] under the provincial *Environmental Management Act*. Testing at least once per year supports classification. “Class A” are re-applied to the land in so-called “beneficial use”. The terminology seeks to promote the reuse of the phosphorus component of the waste. The undesirable components of the waste, like persistent contaminants polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and perfluoroalkyl and polyfluoroalkyl substances (PFAS) remain problematic. Just the largest plant on Annacis Island alone produced 12,000 tonnes of dried biosolids in 2006 (Ashley, 2010). Use of biosolids in agricultural settings have been demonstrated to increase soil, groundwater, and run-off concentrations of PBDEs, PFAS and metals (Gottschall, et al., 2010). Rather than disposing of these contaminants, such methods are dispersing them, creating cumulative risks within soil, and draining waterways.

The focus of classifications is to ensure the reduction of human pathogens and volatile solids, reduction of vector attraction and that metal levels specified in Schedule 4 Quality Criteria are not exceeded. There are no requirements that relate to other potential contaminants such as PFAS, PBDEs, pharmaceuticals, personal care products or microplastics.

Reclaimed water from sewage treatment is permitted for many uses including application to agriculture, provided it complies to standards outlined in the *Municipal Wastewater Regulation* under the *Environmental Management Act* that specify levels of pH, biological oxygen demand, turbidity, residual chlorine, and faecal coliforms[34]. There are no requirements in relation to potential levels of contaminants.

The regulations contain clauses across many areas that provide powers to the Director to not require the application of the regulations under circumstances they deem necessary. Human population has rightly been identified as a threat to the viability of salmon (Hartman, Northcote, & Cederholm, 2013) as the expediency applied to waste management all serve to drive up risks to the aquatic ecosystem’s viability and functionality.

Stormwater

As urbanization progressed so did the installation of hard impermeable surfaces which changed the hydrology of run-off and groundwater recharge. This has the effect of increasing the frequency of high stream flows (flash flood-like conditions) contributing to in-stream damage. Through reduced groundwater recharge it also causes decreased flows during periods of reduced rainfall, resulting in higher temperatures and potential concentration of pollutants. Such impacts were not well managed by municipalities due to a lack of policy and planning around stormwater and its load of contaminants (Nener & Wernick, 1997). Once again, the imperative for economic development to facilitate transport dominated the considerations for construction.

Stormwater, while recognized as a source of pollutants, remains problematic to capture and treat as initial planning did not include space for such activities in urban design, making retrofitting difficult to achieve. Nonetheless some efforts are being made as part of ‘Green Stormwater Infrastructure’ initiatives to improve water quality and stream health in urban areas[35].

---

[33] https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/18_2002

[34] https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/87_2012#section12

[35] https://www.fraserbasin.bc.ca/Green_Stormwater_Infrastructure.html

As outlined above, within the major city area around Vancouver there remain some legacy combined stormwater and sewer drainage systems which discharge poor quality water. Plans to separate these and connect sewerage to treatment plants is ongoing.

Fish processing and canneries

Processing of salmon for export began with 200 barrels of salted salmon shipped from Fort Langley on the Fraser River in 1829.

Commercial salmon canneries were established on the Fraser River in the 1870's after entrepreneur James Syme's canned products won awards at the local agricultural exhibition at New Westminster in 1967[36]. This was at a time before refrigeration was commercially available for preservation of food. The canning industry grew rapidly from 1870 to 1890 with throughput climbing as efficiency was boosted from mechanization. By 1883 there were 24 canneries operating on the Fraser River.

Figure 10: Fishing boats tied up to Canadian Fishing Company Gulf of Georgia Plant cannery c1950 Gulf of Georgia Cannery Society Archives, G2010.027.031

The disposal of offal from processing into the Fraser River adjacent canneries caused localized odor pollution and rendered the water in the river unpotable causing disquiet amongst residents in the 1890s and early 1900s (Mawani, 2009). In June 1906, the commission recommended that "gross violations of the fish offal pollution prohibition in the Fraser River be effectively dealt with by law"[37] The disposal of fish waste (offal) into the adjacent river was linked with squalid conditions and typhoid outbreaks in Steveston from the 1880s to the early 1900s. Offal waste then began to be moved in a scow out into Georgia Strait and dumped there rather than directly into the Fraser River. It was not until the 1930s that salmon canneries began to engineer so called reduction plants to convert the waste offal into fish oil and fish meal to create additional commodities to sell. They also began

[36] http://tidestotins.ca/timeline/

[37] https://publications.gc.ca/collections/collection_2014/bcp-pco/CP32-132-1908-eng.pdf

processing other fish like the Pacific Herring. In the 1940s some plants became entirely focused on converting herring into fish meal and fish oil. There had been sardine (*Sardinops sagax*) reduction plants, established on Vancouver Island in the mid-1920s, but the stock variability saw them close in 1940s.

The cannery industry expanded further by 1901 to 49 cannery camp-villages operating on the banks of the Fraser River between New Westminster and the mouth (Newell, 1994). By 1917 there were 84 canneries in operation in British Columbia with the focus expanding from sockeye salmon to include all five species of Pacific salmon.

Reductions in supply of salmon and demand for canned products combined with industry amalgamations left only 20 fish canneries operating in British Columbia in 1954. The decline of numbers of canneries continued as the popularity and improved logistics favoured frozen product, until in 1996 the last cannery in Steveston, the Imperial Plant, closed.

Some of closed canneries were abandoned, leaching legacy pollutants like discarded oil barrels, asbestos, steel, paint, plastic and creosote-soaked pilings into the Fraser River[38].

Figure 11: A worker slides trays loaded with one pound cans into a retort for cooking. Retorts improved the consistency of cooking, allowing for increased production. Gulf of Georgia Cannery Collection CFC 3-19-3

At the time of the Cohen Commission of Inquiry into the decline of sockeye salmon in 2011 at least 10 seafood processing facilities had permits to discharge effluent into the lower Fraser River. The

[38] https://cvcollective.ca/crumbling-canneries/

contaminants of concern were temperature, pH, total suspended solids, residual chlorine, oil and grease, and nutrients such as nitrate, nitrite and ammonia (Cohen B. , 2012).

Shipping and bulk storage

Shipping began to interface with the Fraser River from the early fur traders in the 1700's. As industry expanded so did the ports to facilitate exports of products from fishing, forestry, and mining.

Today, 24 shipping and bulk storage facilities are in the Fraser River basin, mostly in the lower river and have continued growing over the last two decades. Container terminals are located at Vancouver Port (Centerm, Vanterm, Deltaport), Fraser River Port and North Fraser Port. Port facilities for the very large super-post and post-Panamax sized vessels are in Burrard Inlet, with Panamax shipping able to utilize facilities in the lower Fraser River.

The Port of Vancouver is Canada's largest. It enables the trade of $275 billion in goods to over 170 trading economies around the world[39], contributing $4.6 billion to Canada's gross domestic product (GDP). Fraser River Port contributes $1.3 billion to Canada's GDP serving as a major point of trade for vehicles, forest products, grain, and steel. The North Fraser Port is the major link for transportation of logs for the British Columbia coastal forest industry. It contributes over $1 billion in GDP annually[40]. Contaminants such as petroleum hydrocarbons, anti-foulants and metals can pollute the waters because of this commerce. The considerable freight volumes are moved on road and rail to and from Ports creating more sources of pollution to run-off into the Fraser River.

Shipping also generates a lot of noise in the aquatic soundscape that can interfere with aquatic ecosystem function. Many of these effects are in the lower Fraser River and Strait of Georgia.

The Port is showing some leadership in now running an initiative to reduce its impacts on whales, called the ECHO program. This trial is the slowing down of vessels to reduce underwater noise. The Port is also proactively participating with the Green Marine environmental certification scheme which aims to create stewardship programs to tackle underwater noise, waste management, spills, invasive species, and air pollution generated by the port[41].

Salmon farms

The farming of salmon began in 1972 with marked expansion in the late 1980's to establish cage rearing sites around the Discovery Islands in the northern part of the Strait of Georgia. The industry production rose from 27,000 tonnes in 1995 to average around 73,000 tonnes of salmon from 2011-2015[42], before further expanding to 92,800 tonnes in 2016[43]. The Discovery Islands form a series of passages for wild salmon to migrate northwards out of the Fraser River past the Broughton Archipelago and to the Pacific Ocean. This migration route brings the wild fish into close proximity with the farming activities.

Initially coho and chinook salmon were farmed, however the majority shifted to Atlantic salmon as significant disease issues beset the farmed Chinook.

---

39 https://www.portvancouver.com/about-us/

40 http://faculty.bcitbusiness.ca/kevinw/documents/Fraser_River_SSS_Final.pdf

41 https://www.portvancouver.com/environmental-protection-at-the-port-of-vancouver/leading-with-environmentally-responsible-practices/green-marine-environmental-certification/

42 Farmed Salmon (dfo-mpo.gc.ca)

43 B.C. Seafood Industry - Year in Review 2016 (gov.bc.ca)

From the 1977 significant stock enhancement efforts from hatcheries created new point source pollution sources from chemicals used in rearing such as formalin and chlorine and nutrient enriched wastewater.

A general principle of disease transmission and expression is that disease will be promoted when environmental conditions deteriorate to cause stress. Environmental stress contributes to impairment of the immune defenses of the fish. Hence the complex interplay between the introduction of elevated pathogen (parasites, bacteria and viruses) exposure from high densities of farmed fish, deteriorating water quality (climate change induced warming, sediment elevations, nutrient increases, chemical pollution from agriculture, industry, pharmaceuticals in sewage) create new disease risks to the productivity of wild salmon that require consideration. These expanding human-induced impacts go some way to explain the marine disease outbreaks globally (Tracy, Pielmeier, Yoshioka, Heron, & Harvell, 2019).

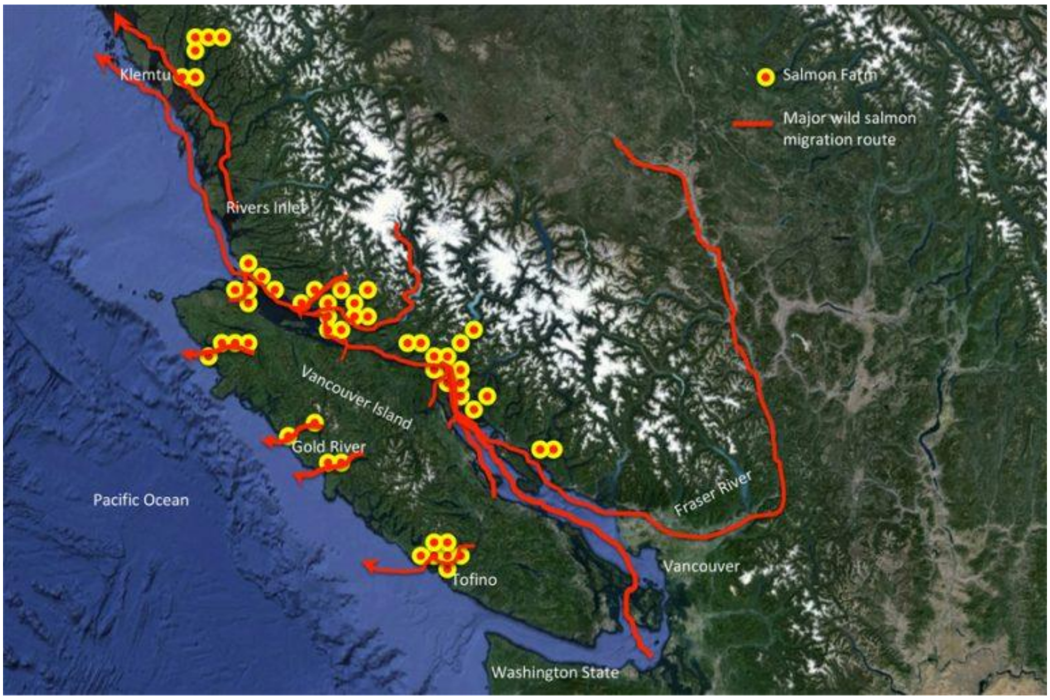

Figure 12: British Columbia fish farm locations and wild salmon migration routes. Source: https://raincoastresearch.org/wild-salmon-science/salmon-farms/where-they-operate/

Sea lice on farmed and wild salmon

Wherever farmed salmon have expanded there has been an associated decline in wild salmon such as Scotland, Ireland, Norway and British Columbia (Ford & Myers, 2008). Experiments in Norway demonstrated 50 times higher mortality of marine phases of Atlantic salmon associated with early sea lice burdens, leading to recommendations to separate farming from wild runs (Bohn, et al., 2020). The role which salmon farming has played in the decline of Fraser River sockeye was examined by the Cohen Commission in 2011 (Dill, 2011).

Farmed salmon when stocked into sea cages are free from sea lice. They acquire infections within months from wild populations of lice which occur naturally on wild and farmed salmon. There is evidence that suggests that the loads of sea lice are increased around salmon farms. The high densities of fish in salmon farms and an array of other factors contribute to farms suffering recurrent infestations that can cause production losses and mortality.

Farmers in British Columbia have responded with different treatment interventions over time that include hydrogen peroxide baths and in-feed treatments of a chemical insecticide, emamectin benzoate, which are released to the local environment. More recently other mechanical de-lousing technologies are being trialed. The effect of releases from an individual farm are not considered to be likely direct or indirect drivers of declines of sockeye salmon (Dill, 2011). However, the cumulative risk from chemical releases from several farms in close proximity remains unstudied, limiting the confidence which can be placed in a conclusion that these releases are not adversely impacting the marine ecosystem (Burridge, Weis, Cabello, Pizarro, & Bostick, 2010).

Figure 13: Sea lice parasites on juvenile salmon Source: Copyright A Morton

From 2004 the Government required farms to treat their fish, whenever the loads of lice exceeded three motile lice per fish during the salmon out-migration (March to June) to reduce perceived risk of impacts spilling onto wild salmon juveniles that were moving to their marine phase of their lifecycle. From 2009 an emergency approval permitted the use of emamectin benzoate as an in-feed treatment for sea lice, which has since been used annually (Saskida, 2015).

The outcome of increased infestation in juvenile, out-migrating wild pink salmon (*Oncorhynchus gorbuscha*) appears to be reduced early survivorship in the very small fish (Krkosek, et al., 2011). Larger pink salmon appear quite tolerant of lice loads and may be the natural host for this parasite. Other scientists have suggested that these early losses of small fish have just replaced other causes of mortality and did not impact the overall survival of pink salmon (Torrissen, et al., 2013).

A nine-year study suggested that where sea lice were controlled better within salmon farms, immediately prior to, and during, the time wild salmon were moving through the farm areas, that lower lice loads were found on the wild fish (Peacock, Krkosek, Proboszcz, Orr, & Lewis, 2013). These researchers observed that the lower lice load correlated to improved pink salmon survival in the returning year class of fish. Other researchers separately analyzed pink salmon return data and farm lice levels to conclude that the number of pink salmon adults returning to spawn in autumn predicts the number of sea lice on farmed fish in the spring, which in turn predicts the lice levels on outgoing wild juveniles. However, they concluded farm lice numbers did not correlate with negative productivity of wild pink salmon (Marty, Saksida, & Quinn, 2010).

The sea lice in British Columbia salmon farms appear to have recently begun to evolve in response to treatments like emamectin benzoate to develop resistance, rendering the treatment less effective as a control on farms (Godwin, et al., 2022).

There appeared to be a synergistic negative impact on early marine life stages of sockeye salmon observed in years where there was high wild pink salmon populations and elevated farm production. The mode of causation was not identified, with significant data gaps impairing further analysis at the time (Dill, 2011).

There are clearly many complex variables that contribute to the population outcomes of salmon with sea lice just one component under consideration in addition to the impact of the farm treatments on wild fish migration and the local food webs.

Diseases of wild and farmed salmon

A range of 46 infectious disease agents were surveyed across 2012 and 2013 in juvenile wild Fraser River sockeye salmon in freshwater and during their marine migration through the Discovery Islands and northwards. It should be noted that some of the fish sampled may come from stocking programs operating throughout the catchment. Elevated rates of infection were identified in 2013, which aligned with elevated Spring water temperatures, and subsequently correlated with poor return rates, suggesting elevated mortality in marine life phase. The elevated infection rates began in freshwater reaches and increased in the marine phase of life cycle (Nekouei, et al., 2018).

The piscine reovirus (PRV) appears to have moved from farmed salmon, internationally to British Columbia Canada and thence become a relatively recent incursion to wild Pacific salmon in British Columbia based on genomic studies (Mordecai, et al., 2021), (Kibenge, et al., 2013). A further investigation of escaped farmed Atlantic salmon (*Salmo salar*) which had been grown from eggs sourced from Iceland suggested their high rate of infection may have been from transmission to the eggs at the source (Kibenge, et al., 2019).

PRV infection has been associated with the disease, heart and skeletal muscle inflammation (HSMI) which has been extensively reported in Norway's farmed Atlantic salmon industry to cause severe disease and mortality outbreaks. In British Columbia's farmed Atlantic salmon PRV infection While common has led to comparatively very low disease rates, without triggering marked mortalities in Canada's farmed Atlantic salmon at this stage (Polinski, Marty, Snyman, & Garver, 2019). However, concerns have been raised that infection of wild Pacific salmon by the virus may be both triggered from interaction with farmed salmon, and that this might reduce fitness of migrating wild salmon thereby reducing their survival and reproduction (Morton, Routledge, Hrushowy, Kibenge, & Kibenge, 2017).

A study on farmed British Columbia Atlantic salmon infected with a local strain of PRV did not identify physiological impairment (Zhang, et al., 2019), however other work on farmed chinook salmon identified the same strain of PRV caused liver and kidney disease in farmed Chinook salmon (Di Cicco, et al., 2018) but not heart disease (Purcell, et al., 2020). Correlations between the prevalence of infection with PRV in early marine phase Chinook salmon and subsequent negative impacts on cohort survival have recently been recently documented (Bass, et al., 2022).

PRV has also been detected in prey species of salmon like herring (*Clupea pallasii*) where some consider it may also be contributing to their decline (Shaffer, 2021).

The role of environmentally relevant mixtures of pollutants altering disease prevalence and severity has been the subject of only limited research. In general, pollution stressors increase disease expression. Farmed fish feeds can contain an array of contaminants from the industrial farming production, storage and manufacture supply chains, such as pesticide residues (e.g. glyphosate, AMPA, paraquat, fenitrothion, pirimiphos-methyl) and industrial anti-oxidants (e.g. BHT, BHA). The effluent from farms will release these and lead to some exposure to the aquatic ecosystems.

Pollutants in Fraser River and adjacent waters

The mainstem of the lower Fraser River has been the subject of monitoring for an array of pollutants emanating from diffuse and point sources. Due to the very large water volumes flowing down the system these studies illustrate similar levels and ranges with the decline of most pollutant concentrations to below levels of detection (Nener & Wernick, 1997). There are some local toxicity effects documented adjacent sewage and stormwater outlets and potential issues where local hydrology may not result in rapid complete mixing. Dilution does not however protect aquatic life from persistent contaminants which can biomagnify and accumulate in aquatic food webs.

The water quality in Lower Fraser River smaller tributaries illustrated a different picture, where mostly diffuse source intensive urban and agricultural use was adversely impacting aquatic ecosystems. In areas that were not populated, forestry activities were the primary activity impacting water quality (Nener & Wernick, 1997).

s Where data was available each chemical was assessed to determine if levels exceeded any toxicological thresholds for aquatic organisms.

Contaminants were identified as contaminants of concern when found at levels above toxicity screening values.

Contaminant type	**Details**
Water quality variable	total suspended solids, pH, turbidity
Nutrients	Nitrate, nitrite, phosphorus
Ions	Chloride, fluoride, sulfate
Metals	Aluminium, arsenic, boron, cadmium, chromium, cobalt, copper, iron, lead, mercury, nickel, selenium, silver
Phthalates	Bis(2-ethylhexyl)phthalate
Phenols and Polycyclic aromatic hydrocarbons	Acenaphthylene, benz(a)anthracene, dibenz(a,h)anthracene

(MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011).

There were stocks such as organometals, cyanides, monoaromatic hydrocarbons, chlorinated and non-chlorinated phenolic compounds, resin and fatty acids, polybrominated diphenyl ethers, hormone mimicking substances, pharmaceuticals, personal care products, wood preservative chemicals and nanoparticles, but insufficient data precluded an assessment of the scale of risk they posed (MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011).

Endocrine disrupting chemicals released from sewage treatment plants were potentially contributing to sub-lethal impacts such as immunotoxicity that may be contributing to the long-term decline of sockeye salmon. The Commissioner considered that exposure to endocrine disrupting compounds may reduce the capacity of smolts to transition from freshwater to saltwater, leading to reduced survival through the marine phase of the salmon lifecycle.

Similarly, contaminants of emerging concern such as veterinary and human antibiotics, prescription and non-prescription drugs, industrial and household waste products, sex and steroidal hormones, herbicides, fungicides, wood preservatives and polychlorinated paraffins were also potentially substantially contributing to declines.

The Cohen Commission report concluded:

"There is a strong possibility that exposure to contaminants of concern, endocrine disrupting chemicals, and/or contaminants of emerging concern has contributed to the decline of sockeye salmon abundance in the Fraser River Basin over the past 20 years." (MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011).

The provincial Land Remediation has around 5000 contaminated sites registered with possibly another 4000 sites yet to be registered as reported in the Cohen Commission (Cohen B. , 2012).

Diffuse source pollution remains poorly quantified and under managed in British Columbia as in the IPEN case studies in Australia's Richmond River and Vietnam's Mekong River. The effects of such pollutant exposures on migratory fish like salmon and eulachon requires complex study designs that need to consider life history, habitat and real-world complex mixtures of contaminant exposures. Where such data are unavailable, the fallback position for managers ought to be deploying the precautionary principle to control exposure to toxic chemical stressors (Ross, et al., 2013). It appears challenging for scientists to generate definitive proof of harm for all combinations of exposures in all life stage relevant trials, prior to collapse of impacted populations.

Sediment

The main river had six different channels between 1827 and 1912 and had deposited a near continuous sheet sand beneath the delta plain. In 1912 the charted water depth in the delta was 2.5m impeding navigable access to the Fraser River. Dredging created depths of more than 12m to facilitate shipping, and has been performed continuously, removing ~2.9Mt per annum (Attard, Venditti, & Church, 2014) since to maintain the channel and supply sand to the aggregate business. Eighty percent of the sediment and all of the sand discharges through the main channel during the few months of the freshet (Barrie & Currie, 2000).

Deposition of natural sediment and sediment from anthropogenic origins into the Strait of Georgia are associated with different subtidal benthic communities. Natural sources of sediment and organic matter support the highest levels of abundance of macro-infauna dominated by bivalves. Whereas polychaete worms dominated areas of elevated anthropogenic organic deposition (Burd, Macdonald, Johannessen, & van Roodselaar, 2008).

Researchers have observed a correlation between the amount of roadway in a sub-catchment and salmon declines. Forestry activities in the upper catchment led to a 20% increase in roads in the upper catchment between 2001 and 2011 leading to increased sediment flows into rivers which can cover spawning areas and reduced available oxygen to incubating eggs. The effects of the forest beetle and salvage logging exacerbate these effects further (Nelitz, et al., 2011).

Nutrient enrichment

The Department of Fisheries and Oceans (DFO) implement shellfish harvesting closures periodically due to suspected or established presence of marine biotoxins[44] in the Strait of Georgia. While these closures generally reflect elevated sea surface temperatures, human pathogens have triggered some closures. The potential foe eutrophication associated with promoting the proliferation of toxic algae remains a concern but, has not been established in this region. Shellfish can bioaccumulate the algal toxins creating food safety risks for human consumption.

Projects in the 1990s identified that agricultural wastes were contributing to elevated ammonia, oxygen depletion and eutrophication in many lower Fraser Valley streams from livestock and poultry effluent and fertiliser use. Groundwater was also found to be contaminated with excessive nitrate levels (The Management of Agricultural Wastes in the Lower Fraser Valley Report 9- Summary Report- A working document, 1997). Excessive application of fertiliser above rates which could be utilised by plants and the importation of feeds to maintain high densities of livestock and poultry were identified as contributory causes.

The economic benefits of agriculture are acknowledged in these Government reports without attempts to enumerate the environmental costs to fisheries from water quality degradation and habitat loss. Thus, the illusion of the high economic value of intensive agriculture becomes a pervasive belief through externalizing the costs from the calculations of benefit. Recent reports into the contaminants associated with the 2021 floods in British Columbia (Ross, Walters, Yunker, & Lo, 2022) lead to a similar conclusion that pesticide-dependent agriculture has contributed to significant degradation of fish habitat in the Fraser Valley.

Wastewater is estimated to contribute to less than 1% of total nitrogen, organic carbon, and oxygen demand into the Strait of Georgia. So, it is unclear if, or how, it contributes to the increasing prevalence of harmful algal blooms (Johannessen, Macdonald, Burd, van Roodselaar, & Bertold, 2015).

Air pollution and climate change effects on salmon life stages

The warming climate is having profound and cumulative impacts on the viability of Fraser River salmon populations in both freshwater and marine phases of their lifecycle. While the severity of effects varies between different runs of salmon, each with varying levels of adaptation, the general impacts in the Fraser River are negative. The cumulative effects are likely to be substantial (Hinch & Martins, 2011).

Greenhouse gas emissions in British Columbia were 57.9 million tonnes of carbon dioxide equivalent in 2018. This was a 7.1% increase on 2007. B.C. has set targets of 16% reduction of emissions by 2007, 40% less emissions by 2030, 60% by 2040 and 80% by 2050, compared to 2007 levels.

The transportation and fossil fuel (natural gas production and processing) sectors generate the most greenhouse gas emissions in B.C.[45].

Water temperatures in the Fraser River have been increasing an average 0.33^{o}C per decade since the 1950s and freshwater is now >2.0^{o}C higher on average than 70 years ago (Hinch & Martins, 2011). The review of the Cohen Commission considered that climate had contributed to decreased survival of

[44] https://www-ops2.pac.dfo-mpo.gc.ca/fns-sap/index-eng.cfm?pg=view_notice&lang=en&ID=recreational&ispsp=1&areas=fraser_river

[45] https://www.env.gov.bc.ca/soe/indicators/sustainability/ghg-emissions.html

smolt, post-smolt, immatures in the ocean and very likely survival of returning adult spawners, with some variation between individual stocks noted.

Climate change appears to also be increasing wildfires and causing more extremes of rainfall. Major floods were reported in 1894, 1948, 1972, 2007 and 2021. 600,000 chickens and livestock perished in the 2021 floods in the Abbotsford area of the Fraser basin. These events are impacting water quality and alter the ability of salmon to navigate to spawning areas, and cause scouring of the riverbed where eggs have been deposited thereby driving greater variability into factors that contribute to spawning success. Low flows, changes in snowpack and melt timing combined with high air temperatures can combine to cause water temperatures above the comfort zone of returning spawner salmon causing them to expend excess energy to return up the river, resulting in higher pre-spawning mortality (Crossin, et al., 2008) and greater risks of increased disease susceptibility (Hinch & Martins, 2011).

The effect on individual salmon stocks varies with when they have naturally returned to spawning areas. Some populations are now entering the rivers 3-6 weeks earlier, which results in exposure to water temperatures 5°C higher than they would have historically encountered. Longer freshwater periods are also contributing to higher disease and parasite infection burdens, as some parasite lifecycles are accelerated by warmer water.

Higher water temperatures also alter the viability of fertilized eggs incubating in gravel sediments. Warmer waters cause faster development, that can result in earlier hatches, resulting in smaller larvae that have less body reserves. The change in timing of hatch may no longer align well with natural feed availability for larvae which historically align with spring blooms (Healey, 2011).

The impacts of climate change are also altering the timing and quantities of rain and snowfall, modifying hydrology in spawning rivers and reducing productivity in nursery lake habitats. Warmer waters in the nursery lakes can lead to earlier and stronger stratification of waters altering the movement of nutrient and reducing the primary production of plankton, thereby reducing the food available to the young salmon (Healey, 2011).

The distribution of predators which compete with salmon appears to be changing in the Fraser River in association with changes to thermal conditions, leading to greater competition (Healey, 2011).

The sea surface temperature in the Strait of Georgia has increased 0.25°C per decade since the 1950s (Cohen B. , 2012). Warming has also been recorded in the marine environments of 0.5°C over the past 2 decades. Warmer temperatures tend to be associated with less upwelling, hence lower nutrient movement to surface, reduced primary productivity and reduced zooplanktonic food for juvenile out-migrating salmon, leading to lower body weight juveniles. The timing of the peak of zooplankton production has advanced up to 30 days, creating a potential mismatch with timing of sockeye salmon migration. The changed temperatures may also be driving mismatches of timing of salmon migration leading to poorer growth and reduced survival through higher predation risks (Healey, 2011). Warming may also be contributing exacerbating toxic algal blooms in the Strait of Georgia.

The sea surface temperatures in the Gulf of Alaska where sockeye salmon grow to adulthood have increased 1.5°C in the past 60 years and 0.5°C from 1990-2010. Much of this has been attributed to the oceanic cycles such as the Pacific Decadal Oscillation, rather than entirely due to climate change (Hinch & Martins, 2011). Warmer ocean conditions appear to align with reductions in food web productivity.

The Fraser River salmon and eulachon fisheries rely on high latitude ocean regions to complete their biological life cycles. These areas have lower levels of seawater saturation with calcium carbonate minerals, rendering them increasingly prone to ocean acidification effects from increasing atmospheric levels of carbon dioxide. The reduction of sea ice and increased rates of primary productivity also force up the rate of acidification (Fabry, McClintock, Mathis, & Grebmeier, 2009) This is likely to alter the composition and location of feed resources, with uncertain effects on those species which have evolved to be reliant upon them on certain geographic migration routes.

Contaminants such as organochlorines, PCBs, PBDEs and metals are known to move thousands of kilometers as atmospheric pollutants (Noel, Dangerfield, Hourston, Belzer, & Shaw, 2009). They can then be deposited into aquatic environments from the top of mountains to the ocean creating exposure risks for migratory species like salmon. Climate change warming is melting glaciers. The meltwater has been demonstrated to be a significant source of organochlorine pesticides in an elevated mountain lake in Canada (Blais, et al., 2001).

Acid discharge, metals mobilization and dissolved oxygen consumption

The Fraser River floodplain contains some acid sulfate soils (Ross & Ivarson, 1981) however they are not as reactive or problematic as those identified in the Richmond River NSW Australia and the Mekong Delta Vietnam.

The major acid discharges come from some mining operations which have been closed, but their tailings continue to generate acid fluxes and mobilize metals into local aquatic food webs. The closed nickel mine near Hope was reported in 1991 to be discharging metal enriched acid tailings water into the Fraser River basin even 20 years after its closure (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998).

Arsenic levels in Fraser River sediments were shown to be elevated likely from anthropogenic sources such as arsenic based wood preservatives and were above federal guidelines and provincial targets in sampling from 1994-1996 (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998). Other metals above provincial criteria were chromium, manganese, nickel and copper, although some of these may be from natural as well as anthropogenic sources.

Current Use Pesticides

After signing the Stockholm Convention and changes to the federal *Canadian Environmental Protection Act, 1999*, Canada moved away from some persistent, bioaccumulative toxic chemicals in favor of more water soluble, less bioaccumulative chemicals including pesticides. These current use pesticides have been detected in agricultural catchment waters that are utilized by salmon. (Harris, et al., 2008) highlighted the need for more research on the impacts to the health of exposed fish, where little to no accumulation of the pesticide occurs.

The effect of organophosphate and carbamate pesticides from agriculture on outgoing chinook salmon juveniles in freshwater has been considered in Pacific northwest USA salmon populations to be a factor that can reduce the size of fish, rendering them less fit to survive once in the ocean (Baldwin, Spromberg, Collier, & Scholz, 2009).

The lack of adequate mixture toxicity data for risk assessment likely leads to underestimates in the risk posed to salmon as some mixtures are additive or synergistic in their toxicity (Laetz, et al., 2009). Mixtures of pesticides at environmentally realistic concentrations have been demonstrated to impair salmon's sense of smell (olfaction), which in turn alter their ability to respond to odors that help them navigate and avoid some noxious threats (Tierney, Sampson, Ross, Sekela, & Kennedy, 2008).

The combinations of pesticides used in salmon farming have been documented in other salmon farming areas to impact the functioning of marine food webs through altering the way ammonia and nitrogen are utilized by bacterioplankton and phytoplankton thereby impacting ecosystem productivity (Valdes-Castro & Fernandez, 2021).

An array of impacts including mortality; reproductive impairment; developmental defects have been identified in non-target marine organisms at exposure levels below those released from salmon treatments. These components of the marine ecosystem have become collateral damage to the enterprise of industrial salmon farms (Urbina, Cumillaf, Paschke, & Gebauer, 2019). Invertebrates appear to be particularly at risk, even at very low exposures.

Use volumes of the herbicide triclopyr in forestry weed control operations correlated with late run sockeye pre-spawning mortality from 1991-1998 (Johannessen & Ross, 2002)

Surfactants (alkylphenol ethoxylates)

The surfactant 4-nonylphenol (4-NP) was detected in Fraser River sediment sampling from 1994-1996 mostly in sites below urban centers. Large known sources of alkylphenols in the Fraser River include pulp and paper mills and sewage treatment effluents, with uses also in plastics manufacturing, cleaners, oil production, pesticides, paints, metal, and leather processing. The highest levels detected were in the north arm of the Fraser River estuary (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998). Around 400-3000T of nonylphenol surfactants alone were estimated to be released from the Fraser River basin annually (Shang, Macdonald, & Ikonomou, 1999).

(Fairchild, Swansburg, Arsenault, & Brown, 1999) suggested that the presence of the spray adjuvant, 4-NP, was the cause of unusually heavy smolt mortality in catchments where it was applied with a carbamate pesticide, aminocarb, as a spray on forestry areas. The adverse impact was believed to be mediated through disruption of the endocrine system of the salmon at a critical transitional life stage of smoltification.

4-NP is recognized as acutely toxic to salmon at parts per billion causing estrogenic effects. It has also been shown to disturb the chemosensory behavior of some fish acting as a neurotoxicant. The interactions of 4-NP with other compounds in water can be complex with a mixture exposure with copper found to ameliorate the impact of 4-NP on chemosensing (Ward, Thistle, Ghandi, & Currie, 2013).

Chemical risk assessments under the Chemicals Management Plan and *Canadian Environmental Protection Act, 1999* assess data on growth, reproduction, and mortality. Ecological risk assessments can consider a wider range of endpoints, that might include neurotoxicity.

Chlorophenols and chloroguaiacols

Chlorophenols from wood preservation operations and Chloroguaiacols from chlorine pulp bleaching were detected in the Fraser River in 1986 and 1988 sampling (Rogers, Birtwell, & Kruzynski, 1990) and remained in sediments below pump mills in sampling from 1994-1996 (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998). Levels in the heavily industrialized and urbanized north arm of the Fraser River estuary remained the highest in the catchment. Other sources in the Fraser River catchment include sewage treatment plant effluents. The chemicals cause immunotoxicity, fetotoxicity and embryotoxicity at low concentrations.

Resin acids released from pulp mills are also detectable in the sediments, however there are not any sediment guidelines to determine if levels are significant contributors to aquatic toxicity. The compounds exhibit some bioaccumulatory potential.

Eulachon migrate up the Fraser River to spawn. The levels of these chemicals in Eulachon correlated with their site up capture upriver, increasing with upriver movement towards sites of pulp mill effluent releases (Rogers, Birtwell, & Kruzynski, 1990).

Mercury and Chlor-alkali plant effluent

A chlor-alkali plant operated in the Squamish River catchment, immediately to the north of the Fraser River from the late 1960's up until 1991. The mercury-cell technology resulted in significant losses of mercury to the environment via plant exhaust and effluent, which While regulated at the time, were subsequently viewed as unsafe, contributing to closure of the plant. An estimated 0.22kg of mercury per day was lost in effluents discharged into the estuary, with 1.3kg per day lost to the atmosphere and another 5.7kg per day lost to unaccounted sources (Thompson, Macdonald, & Wong, 1980). Crabs and bottom dwelling fish were found to have highly elevated mercury levels in the waterway adjacent to the plant (Thompson, Macdonald, & Wong, 1980). A $40 million remediation project for the site which had hazardous waste levels of mercury was completed in 2003 that worked on the site of the plant and 5km into the adjacent estuary, the groundwater remains contaminated with mercury.

Sediment cores collected in the Strait of Georgia, Vancouver harbor and Howe Sound identify historic mercury contamination from 1860, with pulses of input during World War II with a peak attributed to discharges from the chlor-alkali plant into Howe Sound in 1965-1970. No major detectable trends in sediments were reported up to 2005 (Johannessen, Macdonald, & Magnus Eek, 2005).

Mercury levels measured in the hair of harbor seals (*Phoca vitulina*) were up to 8.3ug/g, amongst the highest levels reported in marine mammals in the North Pacific due to the combination of anthropogenic and natural loadings (Noel, et al., 2016).

Salmon can accumulate mercury (Kelly, Ikonomou, Higgs, Oakes, & Dubetz, 2008) and contribute to movement of this contaminant both from freshwater to marine and also in the other direction (Baker, Schindler, Holtgrieve, & St Louis, 2009).

Mercury levels in the eggs of seabirds has not exhibited signs of increases over the period 1968-2015 (Elliot & Elliott, 2016), although the levels in Pacific Ocean water have increased in association with coal burning in Asia (Lamborg, et al., 2014).

Mercury levels in the spiny dogfish (*Squalus acanthias*) were up to 3-4 times above the food guideline level of 0.5 ppm in 1971 sampling, with a notable distribution of higher levels adjacent the Fraser River estuary mouth, suggestive of the Fraser River as a source of the metal (Forrester, Ketchen, & Wong, 1972). The populations of spiny dogfish have been noted to have declined prior to the declines of sockeye salmon (Christensen & Trites, 2011). The impact of such elevated mercury levels of dogfish reproduction has not been studied (Ketchen, 1986), however mercury is known to be toxic to sperm across many vertebrate species.

Pharmaceuticals and personal care products

Increased levels of personal care products and pharmaceuticals were reported in the Fraser River in the 20 years up to the Cohen Inquiry (MacDonald, Sinclair, Crawford, Prencipe, & Meneghetti, 2011). Cocaine, tetracycline, ibuprofen and naproxen were all detected in fish habitat waters of the Fraser River in the recent 2021 flood (Ross, Walters, Yunker, & Lo, 2022). Metro Vancouver finds similar compounds in liquid waste from the major wastewater treatment plants, consistent with findings from other jurisdictions. The consequences of the cocktail of exposures are poorly studied.

Microplastics and adhered toxic contaminants

An estimated 30 billion plastic particles are released annually from a major sewage treatment plant servicing approximately 1.4 million people near Vancouver (Gies, et al., 2018). Within the Strait of Georgia's subsurface seawater 4000-5000 particle per m^3 were detected (Desforges, Galbraith, Dangerfield, & Ross, 2014). Most of these particles consisted of fibers, dominated by polyester, underscoring the link between domestic laundry and the release of microplastics originating from synthetic textiles.

These microplastics were demonstrated to be ingested by zooplankton such as the calanoid copepod (*Neocalanus cristatus*) at 1 particle for every 34 copepods and the euphausiid *(Euphausia pacifica*) consuming 1 particle for every 17 euphausiids (Desforges, Galbraith, & Ross, Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean, 2015). They were also detected inside Chinook salmon at levels up to 2 microfibers per gram of fish (Collicutt, Juanes, & Dudas, 2019)

The marine waters receiving the flow from the Fraser support a significant scale shellfish industry. The use of plastics in this industry result in significant amounts of debris entering the marine environment including styrofoam fragments as buoys break down, trays and crates. Most of the neutrally buoyant plastics appear to be polyester fibres (Vassilenko, et al., 2021) (Ross, et al., 2021)

Road wash-off tires, polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are elevated in sediments in multiple reaches of the Fraser River basin from petroleum and combustion sources above federal guidelines and provincial criteria and regional objectives for protection of aquatic life in sediments in some locations. The concentrations were proportional to the extent of urbanization in each reach of the river, with the highest levels in the estuary from the stormwater and wastewater releases of the large urban area around Vancouver (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998). The upper catchment PAHs had signatures from combustion of wood and grass to the lower urban catchment where vehicle emissions dominate (Yunker, et al., 2002).

Juvenile chinook salmon from the Fraser River were found to have elevated activity in some detoxification pathways suggestive of a biological impact from probable PAH and other toxicant exposure (Wilson, Addison, Martens, Gordon, & Glickman, 2000).

Pink salmon if exposed as embryos to PAHs exhibit lifelong cardiotoxicity reducing their fitness (Incardona, et al., 2015). Chronic exposure to PAHs in the natal habitats leads to reductions in survival of 50% through to reproductive maturity. Simulation models suggest this reduces the growth and stability of pink salmon populations rendering them more at risk should an additional environmental variation occur, pushing them to extinction (Heintz, 2007). Effects have also been reported on early life lipid metabolism impairing fish growth and survival at parts per trillion exposures as embryos within their eggs (Laurel, et al., 2019).These effects of PAHs have been demonstrated to synergize with the effects of climate warming, driving up malformations and mortality in exposed larvae of an arctic forage fish-polar cod (*Boreogadus saida*) (Bender, et al., 2021). Such synergism or additivity of consequences are likely across many species.

Tyre wear particles can be found in stormwater everywhere vehicles are driven. The leachate from these particles have been shown to cause toxicity to returning spawning Coho salmon (*Oncorhynchus kisutch*) leading to elevated premature spawner mortality in addition to mortality to juvenile coho. A wide range of sub-lethal effects in other fish and macroinvertebrates including developmental defects, cardiovascular abnormalities and reduced growth (Peter, et al., 2018) (Tian, et al., 2020) (Chibwe, et al., 2021).

The metabolite of a tyre preservative, 6PPD-quinone, has been identified in stormwater road run-off. The LC50 for coho salmon juveniles was lowered to 0.095µg/L when better laboratory standards were available highlighting that this compound is very highly toxic (Tian, et al., 2022).While no data for levels of the toxin 6PPD-quinone could be found for the Fraser River, data from Toronto, Canada, suggests levels greater than the toxic threshold level of 0.8 µg/L for coho salmon were detected in stormwater run-off during rainfall events (Johannessen, Helm, Lashuk, Yargeau, & Metcalfe, 2022).

Rainbow trout were also identified as sensitive species to exposures of 6PPD-quinone. This may be a component explanation for the decline of the closely related steelhead trout of the Fraser River. However, white sturgeon appeared to be tolerant (Brinkmann, et al., 2022).

Persistent organic pollutants (POPs)

Legacy pesticides- organochlorines

Eulachons in the Fraser River were surveyed coincident with water in 1986 and 1988. DDE and DDD were detected (Rogers, Birtwell, & Kruzynski, 1990).

Organochlorines were still detected in multiple sites in the Fraser River in sampling in 1994-1996 with levels generally declining from prior sampling, but remaining above federal guidelines, provincial criteria, and regional objectives for protection of aquatic life (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998).

PCBs (polychlorinated biphenyls), chlorinated dioxins and furans (PCDD/F)

PCBs were banned as a constituent of any product, machinery or equipment manufactured in Canada from 1980. However, atmospheric deposition, release from transformers and older lamp ballasts and capacitors, historical urban use and run-off remain sources of contamination. PCBs have been detected in pulp and paper mill effluents and sewage treatment effluents, in addition to suspended and bed sediments (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998). Approximately 5% of PCBs that enter the Strait of Georgia originate from the wastewater effluents from the 5 major wastewater treatment plants servicing Vancouver Metro (Johannessen, Macdonald, Burd, van Roodselaar, & Bertold, 2015).

The resident populations of Orcas (killer whales) in the region adjacent the Fraser River contain some of the highest levels of PCBs in the world leading to predictions that the toxic effects causing reproductive and immune system failure may lead to their extinction (Ross, Ellis, Ikonomou, Barrett-

Lennard, & Addison, 2000) (Desforges, et al., 2018). Levels of PCBs in killer whales remain above those anticipated to cause toxic impacts.

PCB trends in the blubber of harbor seals (*Phoca vitulina*) that live locally in the Strait of Georgia from 1984 to 2009 has decreased by 81% (Ross, et al., 2013) (Alava, Lukyanova, Ross, & Shim, 2020).

The blubber of harbor seals (*Phoca vitulina*) indicated significant contamination of 1,2,3,6,7,8-hexachlorodibenzodioxin and 2,3,7,8-tetrachlorodibenzofuran (PCDD/F) in the Strait of Georgia, likely emanated from years of uncontrolled bleached kraft pulp mill effluent release to the aquatic environment. High levels of PCBs probably came from other general industrial activity in the area (Addison, Ikonomou, & Simth, 2005).

Levels of dioxins in sediments were more than 2 orders of magnitude above interim federal guidelines in areas directly below pulp mills at Prince George and Quesnel between 1980 and 1994 (Wainwright, Humphrey, Drinnan, & Fox, 1995) Similarly high levels were detected below the pulp mill at Kamloops. Changes in technology at this mill dramatically reduced the level of PCDD/F emitted by the mill in the 1990's (Macdonald, Ikonomou, & Paton, 1998). Dioxin and furan loadings from pulp mills discharging into marine waters dropped by 97% between 1989 and 1994. Declines of 80-93% were recorded in aquatic biota following the mill process changes (Hagen, Colodey, Knapp, & Samis, 1997). Some of the PCDD/F residues in the lake downstream from the mill appear to relate to wood preservative pentachlorophenol (PCP) use on power poles and railway ties which run along the shores of the lake. Prior to use being restricted in British Columbia at the end of 1990, around half of the annual 750 tonnes of PCP used in British Columbia was applied to cut timber to prevent sap staining (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998).

Sediments in the Fraser River were demonstrated to be contaminated with PCBs, dioxins and furans at levels above federal guidelines and provincial criteria and regional objectives for protection of aquatic life at multiple sites from sampling in 1994-1996. Sites with highest levels were generally below pump mills or urban centers compared to upstream areas. The trend for concentrations was reducing based on historic sampling prior to 1991. However, the north arm of the Fraser River estuary remained highly contaminated (Brewer, Sekela, Sylvestre, Tuominen, & Moyle, 1998).

As sexually mature salmon migrate back up rivers they experience a depletion of lipids from their body. This mobilizes and magnifies the presence of PCB, PCDD and PCDF concentrations in the female gonads by 1.9 to 2.5 fold in sockeye salmon. Longer migration distances lead to much greater concentration. At levels above 3pg/g lipid have been associated with mortality of 30% of eggs in rainbow trout (Debruyn, Ikonomou, & Gobas, 2004).

Where chinook salmon are contaminated with elevated levels of mixtures of PCBs and PAHs their juvenile growth rate is reduced. Reduced growth of juvenile salmon is associated with reduced individual survival and reduced reproductive success (Lundin, et al., 2021).

Brominated Flame Retardants

PBDEs (polybrominated diphenyl ethers)

Widespread use of polybrominated diphenyl ethers (PBDEs) as flame retardants in textiles, furniture, plastics and electronics have resulted in exponential increases in aquatic contamination via wastewater, landfill leachate and atmospheric transport.

Sediments around sewage outfalls around mouth of Fraser River are contaminated with PBDEs. Depending on sediment characteristics these can be bioavailable and are in turn able to be detected in biota such as deposit and filter feeders (bivalves and polychaetes) and in higher concentrations in predators of these that feed in these areas such as crabs, benthic fish and seals (Burd, et al., 2019). More than 60% of the PBDEs in the Strait of Georgia come from wastewater discharges of the five major Vancouver metro wastewater treatment plants (Johannessen, Macdonald, Burd, van Roodselaar, & Bertold, 2015).

PBDE's showed increasing concentrations in the blubber of harbor seals from 1984-2003 by 99% before plateauing. PBDE's have only recently been phased out in Canada. Concentrations appear to be dropping in seal blubber from 2009, reflecting the removal of penta- and octa- formulations from the market in 2004 (Ross, et al., 2013), (Alava, Lukyanova, Ross, & Shim, 2020). Some Canadian data contributed to subsequent listing of Penta[46] and Octa[47] BDE starting around 2009 after nomination by the EU and Norway in 2005. BDE-209 was later listed on the Stockholm Convention in 2017 again with data contributions from Canada[48].

Coastal seabirds are also sensitive species to monitor for PBDE's in their eggs. Increases were documented in monitoring between 1979 and 2000 in great blue herons (*Ardea Herodias*) and double-crested cormorants (*Phalacrocorax auratus*) followed by declines after 2000 of major congeners (Miller, et al., 2015). The declines in birds and seals (Ross, et al., 2013) are suggestive that Canadian regulations to control their production are working.

The aquatic environment is accumulating large volumes of BDE-209 (main component of deca-BDE) as it partitions to sediment. It breaks down into more bioaccumulative, toxic and mobile PBDE congeners in the environment posing risks to the aquatic ecosystem through triggering endocrine impacts on development, reproduction, behavior, and physiological function (Ross, et al., 2009).

HBCDD (hexabromocyclododecane)

Hexabromocyclododecane (HBCDD) was used in building insulation foams. It was banned in Canada in 2016 when added to the Toxic substances list. It was not detected prior to 2003 in eggs of great blue herons (*Ardea Herodias*) and double-crested cormorants (*Phalacrocorax auratus*) in the Salish Sea area but has been detected at low levels subsequently up to 2012 (Miller, et al., 2015).

PFAS (Polyfluorinated alkyl substances)

Perfluorooctanoic acid (PFOA) its salts and PFOA-related compounds are listed on Annex A of the Stockholm Convention for elimination. Perfluorooctane sulfonic acid (PFOS), its salts and

46 https://chm.pops.int/TheConvention/POPsReviewCommittee/Reports/tabid/2301/ctl/Download/mid/7538/Default.aspx?id=266&ObjID=4842

47 https://chm.pops.int/TheConvention/POPsReviewCommittee/Reports/tabid/2301/ctl/Download/mid/7538/Default.aspx?id=398&ObjID=5341

48 https://chm.pops.int/TheConvention/POPsReviewCommittee/Reports/tabid/2301/ctl/Download/mid/7538/Default.aspx?id=16&ObjID=19071

perfluorooctane sulfonyl fluoride (PFOSF) are listed on Annex B of the Stockholm Convention for restriction of production.

Restrictions on the use of some polyfluorinated alkyl substances (PFAS) have been introduced in Canada, but they are yet to reduce levels measured in wildlife such as sea birds, where levels of perfluorohexanoic sulfonic acid are increasing in eggs of rhinoceros auklet (*Cercohinca monocerata*) and leech's storm petrel (*Oceanodroma leucorhoa*) (Miller, Elliott, Elliott, Lee, & Cyr, 2015).

In June 2022 US EPA lowered the drinking water lifetime advisory level to 4pg/L (0.000000000004g/L) for PFOA. Danish EPA in 2021 tightened their limit to 2ng/L of sum of 4 PFAAs (PFOA (perfluorooctanoic acid), PFOS (perfluorooctanesulfonic acid), PFHxS (perfluorohexanesulfonic acid) and PFNA (perfluorononanoic acid)). The level in rainfall globally is now considered to be widely above these levels (Cousins, Johansson, Slater, Sha, & Scheringer, 2022).

An indoor air study in Vancouver homes identified elevated levels of PFAS in air likely originating from a range of consumer products (Shoeib, Harner, Webster, & Lee, 2011). The location of elevated PFAS in the Fraser River aligns with this urbanized pattern of emissions as waterways that drained urbanized sites showed higher levels of contamination. Phase-outs and regulations have not consistently resulted in expected reductions of levels of detections over time (Gewurtz, et al., 2013).

Commercial fishing industry of Sockeye salmon and historical abundance

The Sockeye salmon (*Oncorhynchus nerka*) formed the basis for the commercial fishing industry that expanded with European, Chinese, and Japanese settlers from the 1870's. Prior to this time there had been substantial and sustained harvesting by First Nations people for thousands of years.

The catches by early settlers of 35-50 million Fraser River salmon in 1901 demonstrate the abundance of sockeye prior to colonial settlements. The dominant run every fourth year was in the order of 100 million prior to 1913 (Ricker, Effects of the fishery and obstacles to migration on the abundance of Fraser River Sockeye Salmon (Oncorhynchus nerka), 1987).

The exploitation of the abundant salmon resources quickly resulted in the development of salmon canneries in 1870 which preserved the product to facilitate transport to export markets around the world.

Figure 14: Unloading salmon catch to Dumfries Cannery on the Fraser River c.1890, Image CVA 256-02-10 courtesy of the City of Vancouver Archives

The first salmon hatchery was established on the Fraser River at New Westminster in 1883 to address the issue of declining salmon stocks and sought to increase the number of salmon returning to the Fraser River. Government measures were enacted around 1889 to address declining stocks by decreasing the number of fishing licences. [49] The Wilmot Commissions of 1890 and 1892 led to regulation of boats, canneries, fishing net sizes and annual closures to protect the stock.

[49] http://tidestotins.ca/timeline/

Figure 15: Large numbers of fishing skiffs in the mouth of the Fraser River catching salmon c.1890 Image B-07395 courtesy of the Royal BC Museum and Archives

At canneries the fish were packed into one-pound tins, with 48 tins then packed into a case, which became the unit of output for the fishery. From 1875-1898 the combined take was less than 200,000 cases per year. The catch boomed as fishing effort expanded with introduction of the gasoline engine in 1900 to the Fraser River fishing fleet, to an all-time maximum of 2,392,895 cases in 1913 by which time 80% of the fleet were gasoline powered.

Figure 16: Salmon catch awaits processing at a Fraser River cannery, 1913. Image E-05031 courtesy of the Royal BC Museum and Archives

The construction of an inland railway through a steep canyon area of the Fraser River's descent is believed to have contributed to a major landslide in 1914 that led to accelerated water velocities through the long narrow stretch of river known as Hell's Gate. The timing appeared to exacerbate an already difficult passage year when river flows were already very high. The water velocity was such that most of the returning adult salmon were unable to penetrate through it to their upstream spawning grounds, with millions of fish dying below the blockage, before having had the chance to spawn the future generation of salmon. The failure of recruitment of new juveniles led to a massive 70% collapse in the catches in the following years.

Figure 17: Clearing rock slide at Hells Gate, Fraser River circa 1910-1920 Source: Major Matthew Collection, Vancouver City Archives A-8-3.2

Figure 18: Fraser River Hells Gate, with constructed fish ladder visible on righthand side of river. Source: https://commons.wikimedia.org/wiki/File:Hell%27s_Gate.jpg D Harvey Creative Common Attribution-Share Alike 3.0 Unported license

The fishing industry continued to modernize and increase efficiency through the 1920's with the advent of refrigeration and the innovation of the powered drums to haul gill nets in 1931.

Both Canadian and American fishers had a significant commercial stake in the salmon fishery and concerns over its depletion. The US Congress subsequently passed the White Act in 1924 which required at least 50% of an individual salmon run be allowed to return and spawn. In 1930 the Pacific Salmon Treaty was signed and then ratified in 1937 between Canada and the United States. The International Pacific Fisheries Commission oversaw the operation of the Treaty driving further restoration and propagation works in the Fraser River catchment to try and ensure adequate numbers of fish were able to return to sites in the catchment to spawn. It also created a system for accurately recording commercial catches, using observers.

In 1942 soon after Japan bombed Pearl Harbour and USA declared war on Japan, the Canadian Government ordered all Japanese people, including 1800 employed in fisheries to be removed from within 100 miles of the B.C. coast. All 1337 of their fishing boats were seized. They were not allowed to return to the coast until 1949[50].

[50] http://tidestotins.ca/event/japanese-internment/

In 1945, the International Pacific Fisheries Commission concluded that the cause of the sockeye salmon fishery decline was either due to commercial overfishing, or the result of a landslide, which had altered the ease with which fish could access the upper catchment spawning areas.

Engineering works, such as fish ladders, to facilitate upriver fish access were installed. Immediate benefits were reported in 1945-46 to fish accessing spawning areas. Greater controls were also placed on fishing effort to control catch.

The extent of the improvement, off the very low base, achieved over the next 9 years was remarkable and illustrative of the extent to which habitat access was restricting numbers of salmon. Under controlled fishing effort through the 1950s, the fishery recovered some productivity, albeit at a lower level than the pre-1913 era.

The catches were noted to be highly correlated to the numbers of juvenile fish which ran back down the Fraser River to head off for the marine phase of their lifecycle.

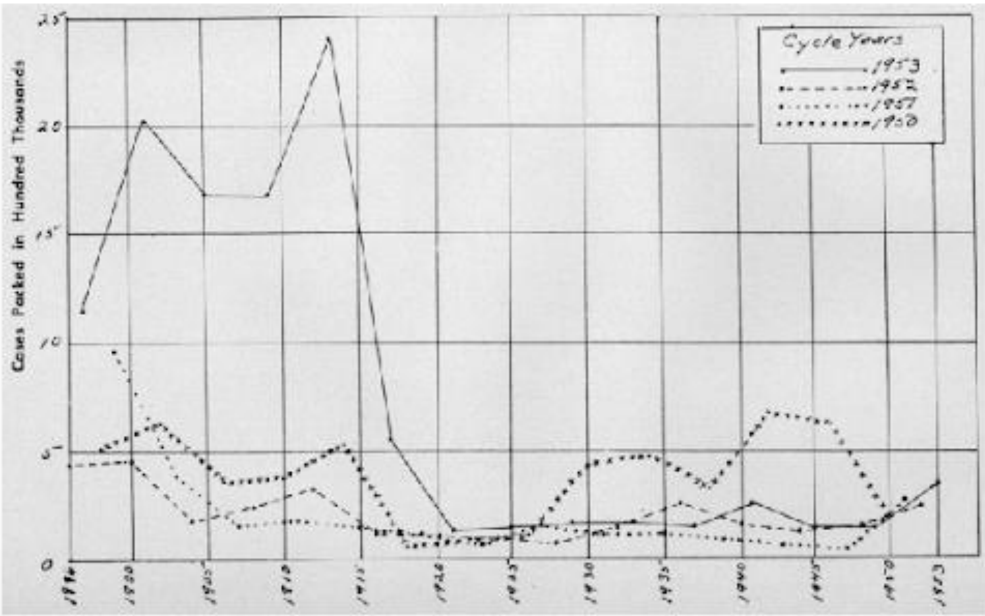

Figure 19- Pack of Fraser River Sockeye by Cycle years (48-pound cases) (Merriam, 1954)

**BREAKOUT BOX

Canadian fisheries scientist W. E. Ricker wrote in 1954 that even in the absence of fishing, fish populations tend to fluctuate about some level maintained by natural controls. He proposed a reproduction curve which illustrated the number of recruits that might be expected, relative to the numbers of spawning fish, which was subsequently used as a tool to estimate the maximum sustainable yield from the fishery. Importantly the relationships assumed that the environment remained stable through the period of observations (e.g. habitat, climate and fishing conditions) (Ricker, 1954).

The assumption that was perhaps apt in 1954. The environment has undergone radical change since that time, so the previously understood relationship between numbers of returning spawning fish and the numbers of fish that flow through into the fishery has broken down.

CLOSE BREAKOUT BOX**

The drivers of the recovery were highly correlated to removal of barriers to adult fish upstream movement to their spawning grounds. It was recognized that in years of very high flows, engineered works could facilitate the otherwise retarded upstream movements. This included removal of Hells Gate landslide material in 1914 and creating passage past a dam at Lake Quesnel in 1921. The installation of fishways (a series of vertical concrete baffles to create places for the salmon to rest on their upstream movement) through the high velocity Hell's Gate river section, and another area further upstream in 1945-1946 and a high-water level fishway in 1951. Upstream areas which had become barren, were restocked.

A tripartite agreement was signed in 1953 between Canada, United States and Japan to manage Pacific Salmon stocks in each country.

Through this time catches were restricted to ensure plenty of fish made it to the spawning grounds and contributed to substantial numbers of juveniles returning down the river. While the fishery has not recovered to the peaks of the early 1900's, it remained the world's largest single river producer of the pacific salmon species up to the late 1990's (Northcote & Atagi, 1997).

Research at the Quesnel field state supported by the International Pacific Salmon Fisheries Commission in the early 1950s leads to the construction of the first artificial spawning channel in 1954 for pink salmon. Subsequently five more channels are constructed between 1963 and 1973.

In 1977 the British Columbia Salmonid Enhancement Program was established in an attempt to expand production of salmon for commercial fishers. By 2011 there were 23 major enhancement facilities and spawning channels managed by government employees and 21 community hatcheries with a further 350 public involvement projects supported by 18 DFO community advisors (Stephen, Stitt, Dawson-Coates, & McCarthy, 2011).

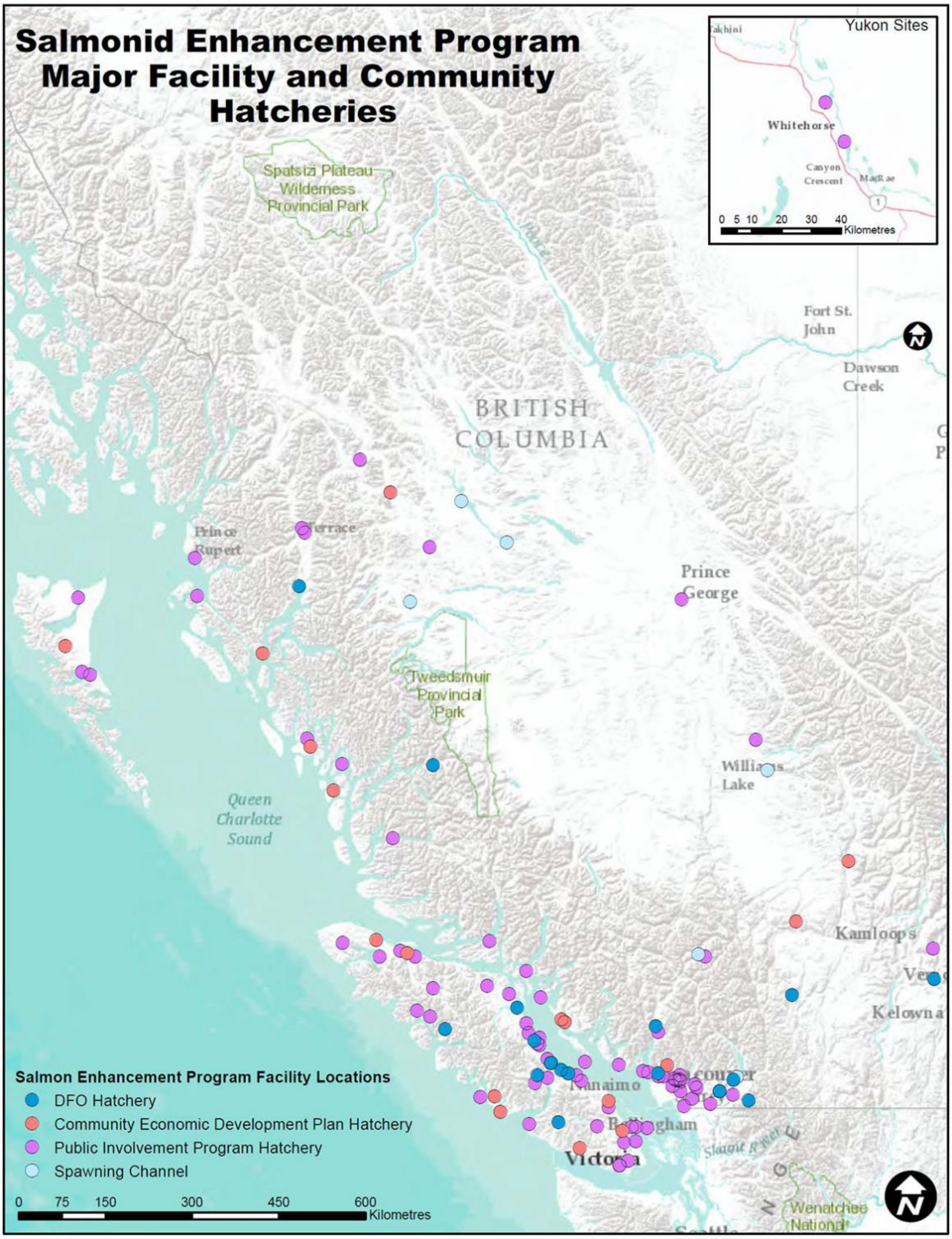

Figure 20: Map of salmonid enhancement program major facilities and community hatcheries Source: https://www.pac.dfo-mpo.gc.ca/sep-pmvs/docs/hatchery-map-carte-ecloserie-eng.html

In 1985 the Pacific Salmon Treaty between Canada and the United States was signed to conserve and manage Pacific salmon stocks[51] which operated until disagreements around coast-wide fisheries arrangements from 1992-1998. These were resolved and created long-term arrangements for the Fraser and Yukon systems. In 2009 salmon outside these two systems were included in the sharing

[51] https://www.psc.org/publications/pacific-salmon-treaty/

arrangements. The Pacific Salmon Commission provides weekly updates of the status of the fishery including the estimates of the run size compared to pre-season expectations and estimates of migration timing compared to pre-season expectations[52].

From 1950's to 1990's pink and sockeye salmon returns to their spawning grounds in freshwater increased.

Coho salmon however, suffered nearly eightfold declines with worst impacts seen in the coastal populations. Over-fishing and loss of habitat were reported to be major contributors to the decline (Harding, Jaremovic, & Kosakosko, 1994).

Chum salmon (*Oncorhynchus keta*) were considered an important winter staple for First Nations people in the 1800s and early 1900s. Dredging of rivers and forestry impacts are considered to have impacted these populations even prior to fishery records (Morin & Evan, 2022). Populations were considered depressed in the Fraser River prior to the 1980s which triggered major stock enhancement efforts from four major hatcheries and other community enhancement projects to boost production for commercial, recreation and First Nations uses. From 1953-1980 an average of 0.63 million chum salmon returned which rose to an average of 1.67 million between 1981-2005. Around 35% of this was due to stock enhancement activities- which underscores the loss of productivity of this part of the lifecycle in the wild fishery. The abundance of fish was considered healthy enough in 2009 not to warrant a legislated level of protection. Chum salmon appeared to be less impacted compared to other salmon species by years of low marine productivity up to 2007 (Grant & Pestal, 2009).

By 1996 likely more than 100-200 runs of Pacific salmon were already extinct particularly in the southern part of their range in British Columbia (Slaney, Hyatt, Northcote, & Fielden, 1996)

In 1997 Canadian commercial fishers took more than 12 million salmon, American commercial boats took more than 3 million and the First Nations fishery took just over 1 million[53].

The coho and other salmon stocks historically used the Strait of Georgia as habitat and for its historically abundant prey species food resources. The salmon were also targeted there by sport and lure trolling fisheries, but during the 1990's they left this area (DFO, 2001).

The change in salmon behavior aligns in timing with changes in the water conditions in the Strait of Georgia.

Agricultural intensification and runoff, sewage and aquaculture inputs all enrich the nutrient loadings in the receiving Strait of Georgia (Hall & Schreier, 1996). The bottom waters of the Strait of Georgia have been noted to be declining in levels of dissolved oxygen since the 1970's to levels which can seasonally threaten aquatic life. The greatest contributor to the oxygen decline in deep basins is changes in oceanic upwelling altering the flow of low oxygen water into the Strait (Johannessen, Masson, & Macdonald, 2014). However, local nutrient inflows can be important drivers of algal blooms and deoxygenation (Khangaonkar, et al., 2018). The role of chronic high levels of aquaculture effluents in contributing to lowered oxygen levels has been clearly identified in other countries including Australia (Maxey, Hartstein, Then, & Barrenger, 2020) and Japan (Gao, Zhou, Dong, & Kitazawa, 2022).

---

[52] https://www.psc.org/publications/fraser-panel-in-season-information/sockeye-and-pink-salmon-in-season-status-reports/

[53] https://www.theglobeandmail.com/news/national/the-story-of-the-fraser-river-a-symbol-of-life-that-can-also-be-violent-and-deadly/article31403733/

Relatively rapidly annual exchange of water between the ocean and the Strait of Georgia are considered to make large scale eutrophication unlikely (Mackas & Harrison, 1997).

Expanding climate-change influenced impacts through the 1990's appear to have also promoted formation of larger toxic algal blooms of *Heterosigma akashiwo* through influencing stratification from massive freshwater flows, lower winds and increased entry of nutrient rich upwelling currents. Heterosigma blooms became near annual events (Brown, Haigh, & Johnson, 2018), which depending on their density were in turn were reported to be impacting the survival of prey species for salmon such as herring (Rensel, Haigh, & Tynan, 2010). These effects were reported to be magnified in 2007 when dramatic declines in marine survival of all salmon were reported consistent with a lack of prey in the critical early marine phase within the Strait of Georgia (Beamish, Neville, Sweeting, & Lange, 2012). The presence of harmful algal blooms in the Strait of Georgia remains variable with complex drivers contributing to toxin accumulation in shellfish and impacts to wild and farmed fish (Esenkulova, Suchy, Pawlowicz, Costa, & Pearsall, 2021).

Coho salmon were considered to be declining due to a combination of overfishing and habitat loss. Logging, road construction and associated forestry activity affect stream hydrology, channel stability and increase sedimentation (Harding, Jaremovic, & Kosakosko, 1994). Coho salmon were found to be highly sensitivity to a toxin (6PDD-quinone) from road tire breakdown that washes in with rain causing acute mortality (Tian, et al., 2020). This factor may have contributed to their declines, as an association with the number of roads in their sub-catchments was identified (Harding, Jaremovic, & Kosakosko, 1994). Stocks today are supplemented with hatchery reared coho. The Department of Fisheries and Oceans (DFO) Canada hatcheries also rears chum, chinook, sockeye, and rainbow trout (steelhead) for stocking[54]. Spawning channels have also been constructed in some locations to provide habitat for spawning and egg incubation. In aggregate these are estimated to release close to 400 million juvenile salmon annually.

The potential role of salmon farms in altering wild salmon productivity is discussed in prior section of the report, as the farms developed in the migration path of the wild salmon through the 1980s and 1990s. Ongoing fierce debate between pro and anti-salmon farming groups over the impact of farms on wild salmon culminated in a Fisheries Minister mandate letter requiring the transition of open-cage fish farming out of British Columbia waters by 2025.

The use of sonar and acoustic monitoring 2009 cycle saw a record low count of only 1,590,000 adult sockeye returning to the Fraser. This was the second lowest return on any cycle since the commencement of record keeping in the late 1800's[55]. For sockeye salmon the decline of stocks in the Fraser River became so remarkable that a $27 million (Canadian dollars) Government Cohen Commission of Inquiry was established to investigate the decline in 2009. The Commission engaged experts to research various potential contributing causes including: diseases and parasites; effects of contaminants; freshwater ecology and status of Conservation Units, marine ecology; impacts of salmon farms; fishery harvest and management; predator effects; climate change effects and habitat analysis.

The longer the migration distance of the sockeye stock in the Fraser River, the greater the decline observed from the 1990s onwards.

Unexpectedly, the 2010 return was massive with 28,200,000 sockeye returning.

[54] https://www.pac.dfo-mpo.gc.ca/sep-pmvs/hatcheries-ecloseries/index-eng.html
[55] https://www.psc.org/about-us/history-purpose/our-history/

The Cohen Commission concluded that the decline of Fraser River sockeye salmon was complex with many factors potentially contributing. Justice Cohen made 75 recommendations which have subsequently guided many actions of DFO to try to protect and restore populations[56].

After 2010, the downward trend quickly returned to reach a new record low in 2016 (Figure 21).

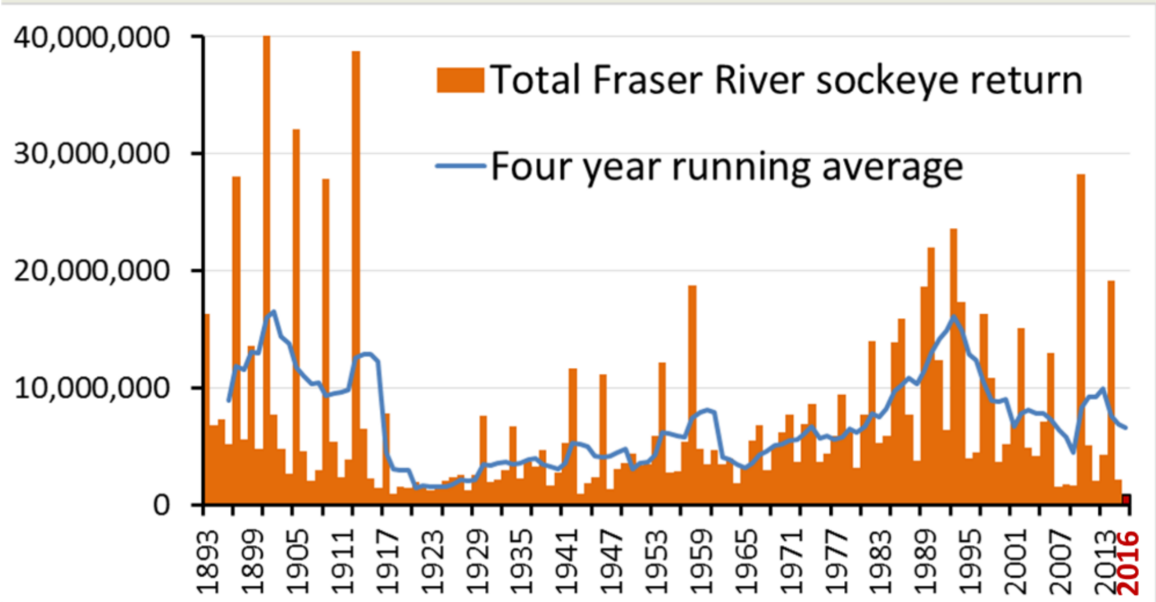

Figure 21: Sockeye salmon returns to the Fraser River 1893-2016 Source: https://www.psc.org/about-us/history-purpose/our-history/

Current status of Pacific salmon

In 2018 a new low was reached with 855,000 sockeye salmon returning, then only 493,000 in 2019 with the numbers of returning sockeye estimated to be only 291,000 in 2020. A major landslide in the Big Bar area which was detected in mid 2019, impaired migration for around 80% of returning sockeye and upper Fraser River salmon populations. High water flows through the big bar landslide were reported to have contributed to lower spawner returns in 2019 and 2020.

[56] https://www.dfo-mpo.gc.ca/cohen/annex-annexe-2018-eng.htm

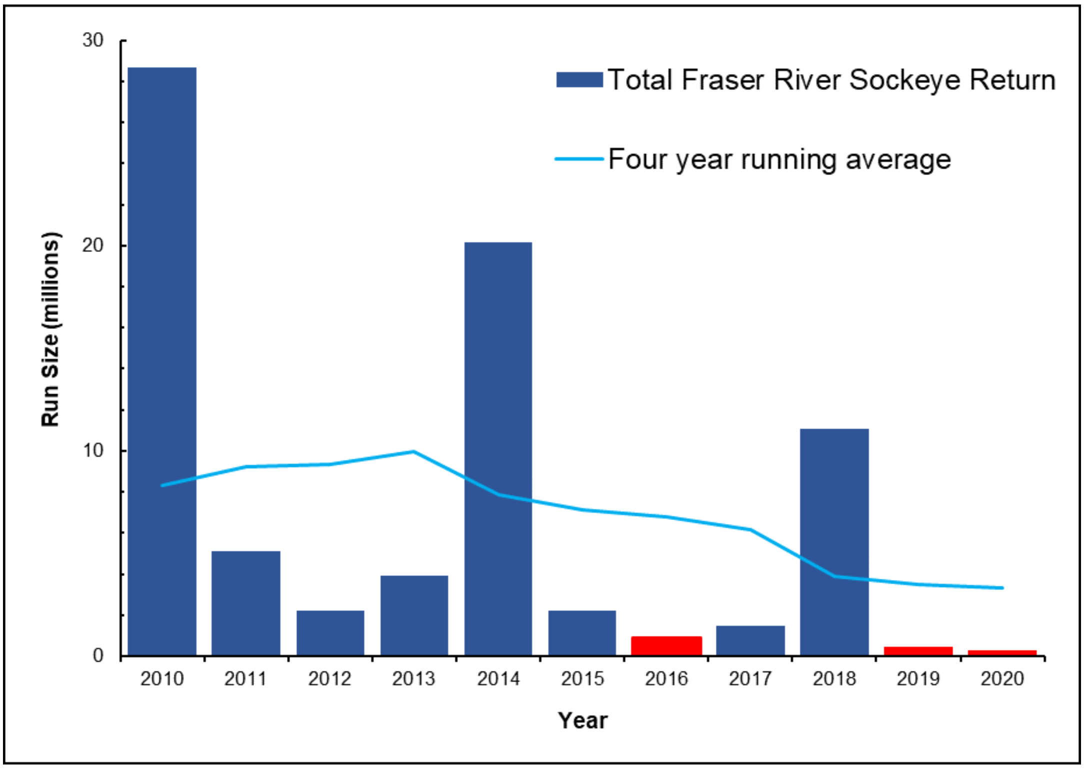

Figure 22: Sockeye salmon returns to Fraser River 2010-2020 Source: https://www.psc.org/about-us/history-purpose/our-history/

Prompt actions by First Nations experts, and the provincial and federal Governments, to helicopter lift broodfish above the waterfall and improve natural passage through maneuvering rocks in the river allowed some 276,000 fish to get through the area in 2019. In 2020 a concrete fishway was installed and a pneumatic fish pump was installed and trucking capability. Some broodfish were also collected at the blockage and transferred to local hatcheries run by First Nations, community partners and DFO to generate some juvenile fry for restocking.

An increase was recorded in 2021 to 1.5 million however this was still 64% below the historical cycle line which averaged 7.08 million returning spawners[57]. The commercial fishery did not participate in any substantial fishing of the stock under DFO management. Only two licences for Food Social Ceremonial fisheries were issued in terminal areas. There has been no commercial fishing at this stage in 2022. This is reviewed weekly and should returns exceed expectations then some commercial fishing may be opened.

The extent of this decline is striking compared to the estimated size of the dominant run of sockeye prior to colonial settlement of 100 million salmon (Ricker, 1987).

Poor survival in both the freshwater phase and the marine phase was associated with elevated water temperatures being attributed to poorer productivity in the river and ocean.

Understanding the multifactorial causes of decline requires understanding the underlying mechanisms in each of the habitats that the salmon pass through. The available knowledge of ecosystem resources and interactions was insufficient in the conclusion of the Cohen Commission in 2011 (Christensen & Trites, 2011). It remains an aspiration to coordinate to collect better ecosystem level data.

[57] https://upperfraser.ca/docs/newsletters/2021_Post_Season_2022_Outlook_Summary.pdf

Pink salmon returns in 2021 were 7.99 million which is 30.5% below the historical cycle line of 11.49 million[35]. Some commercial, recreational and food social ceremonial fisheries operated on the Lower Fraser River.

Chinook salmon productivity in 2021 remains very low. Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessment identified 10 groups of Chinook stock were considered endangered, 4 threatened, 1 of special concern and 1 not at risk. DFO considers that climate change, ecosystem modification, fishing impact and competition with hatchery fish may be impacting Chinook survival[35].

Coho salmon populations in 2021 have remained low, even though exploitation has been low since introduction of management measures in 1990s. Smolt to adult survivals have been low suggesting altered ocean productivity affecting the marine phase[35].

Chum salmon returns have fallen well under predictions since 2017 resulting in closure of most of the recreational and commercial fisheries. Some limited First Nations food, social and ceremonial catch was permitted. Fish size at age in 2021 was lower than average (Fisheries and Oceans Canada, 2022).

It is interesting to compare to the current plight of the salmon, with the stock collapse from fish passage blockages in 1914. Differing drivers of modern declines in salmon with habitat loss, pollution, and climate driven shifts in marine productivity all prominent. The small streams alone that percolated through where the city of Vancouver now bustles once supported up to 200,000 salmon, today they support close to zero (Morin & Evan, 2022).

As this report explains, the addition of pollution-based factors over time are probably contributing to the array of anthropogenic factors contributing to the decline of salmon. In 2011 the Cohen Commission noted that contaminant effects were commonly sub-lethal rendering sockeye more susceptible to disease and predators. These effects were exacerbated when fish were challenged with other environmental factors such as high-water temperature or nutritional stress. DFO acknowledged contaminants including pesticides may potentially affect Fraser River salmon. A lack of data precluded clearer assessment of the role of contaminants in the decline (Cohen B. , 2012). Dr Peter Ross, an expert in marine toxicology, testified that contaminants were very likely to have contributed to the long-term decline of salmon through death by a thousand cuts impacting their resilience.

** BREAKOUT BOX**

Perhaps the hopes of the 1952 Commission were too optimistic, as expressed in quote below, about the ability of management to control impact of development when they identified that:

"*Thousands of acres of potential agricultural lands needing pump irrigation are considered feasible for use without endangering the fish program. Lumber companies are asking for more and more timber to cut, planning to exceed the billion board feet cut in 1951. Settlers are slowing coming into the watershed areas. In British Columbia and estimated 15,000,000 horsepower of hydroelectric energy, half of it in the Fraser Basin, could be developed without hindering the salmon program, if properly planned. Even pulp mills could be encouraged if the problem of waste disposal is properly handled."* (Merriam, 1954)

Some of these visions have come to pass - agriculture has expanded with irrigation, more timber has been cut by forestry and many pulp mills were developed. Hydroelectricity has not become a feature of the Fraser basin.

The waste problems from all these industries and substantial urban development have been subject to regulation. Although it can be argued the design of regulation and enforcement has always been inadequate to fully protect aquatic ecosystems. The desire to sustain and protect the salmon fishery has been earnest throughout time. It appears that the once great salmon fishery has become collateral damage to the consumptive economic priorities of industry and Government which have generated its 'death by a thousand cuts'. The pacific salmon, and other fish species of the Fraser River have declined dramatically even as the stringency of regulation improved environmental protection over time and scientists better appreciated the contributing factors to decline.

CLOSE BREAKOUT BOX**

DFO released the Wild Salmon Policy in 2005 which was intended to transform management and apply the precautionary principle. In its 2012 final report the Cohen Commission noted that the policy appeared not to have ever been fully costed, and seven years after its release was largely unimplemented (Cohen B. , 2012). Recommendations were made to DFO to cost and allocate funds specifically to implementing the policy. Another five years on, and there was still no quantification or commitment of funding, and implementation was far from complete. The trend of declining assessment of the numbers of returning salmon to many streams, with around 30% unassessed, impairs the ability of fishery managers to predict and thus manage the fishery (Price, English, Rodenberger, MacDuffee, & Reynolds, 2017). The Wild Salmon Policy implementation plan was finally created in 2018 and increased funding allocation made to try and protect and restore remaining pacific salmon populations with increased transparency to the public promised[58]. Ongoing actions are found in the DFO Wild Salmon Policy 2018-2022 Implementation Plan [59]. The stated aim is: "To restore and maintain healthy and diverse salmon populations and their habitats for the benefit and enjoyment of the people of Canada in perpetuity". Key themes are Assessment, Maintaining and Rebuilding Stocks and Accountability.

The Government launched a $647 million program in June 2021 to stem the historic declines of Pacific salmon stocks to rebuild them to sustainable levels through conservation and stewardship; salmon enhancement (restocking); harvest transformation; and integration and collaboration. This has included voluntary commercial fishery licence retirement programs to transition to a smaller commercial harvest sector.

Even after years of very substantial investment the prediction for 2022 is sobering:

"Climate change is driving a broad trend of salmon decline….. This is expected to continue. Salmon productivity is generally below historical averages (exceptions and conditions vary by population). The future for salmon will depend on how successfully we can curb greenhouse gas emissions."[60]

It becomes clear that global management of transboundary pollutants is essential if the dividends from federal, local provincial and First Nations restoration efforts are to be fully realized.

Eulachon (*Thaleichthys pacificus*)

Eulachon are an anadromous (moving between freshwater and marine water) smelt. In the wider ecology they are recognised as a foundational ecological species forming food for a wide range of

[58] https://www.pac.dfo-mpo.gc.ca/fm-gp/salmon-saumon/wsp-pss/ip-pmo/index-eng.html
[59] https://www.pac.dfo-mpo.gc.ca/fm-gp/salmon-saumon/wsp-pss/ip-pmo/index-eng.html
[60] https://upperfraser.ca/docs/newsletters/2021_Post_Season_2022_Outlook_Summary.pdf

predatory species in the ocean including salmon, whales, sea lions, seals, otters, dolphins, and seabirds. The fish have a short life cycle spawning in freshwater. The eggs adhere to river sediments. Upon hatching the larvae are rapidly flushed to the estuary before moving seawards for 2-5 years. They occupy offshore benthic habitats in 50-200m of water. When they reach sexual maturity they head back to freshwaters to spawn their eggs onto sandy gravel substrates. The adult fish then die at around 160-250mm in length.

The species was seasonally hyper abundant in the Fraser River where runs were reported to contain one to two thousand tons of fish (Morin & Evan, 2022).

Eulachon rely on phytoplankton and zooplankton such as copepod, mysid, ostracod, barnacle larvae and euphasiids, as feed resources.

They are referred to by some First Nations people as the “salvation fish” for their abundance in rivers often timed with a shortage of other fish resources. The First Nations Fraser River fishery has recorded minimal catch in recent years for the species which has historically been used for food, social and ceremonial purposes through smoking, drying, salting, and making into grease due to the fishes very high fat content when spawning. The grease was a valuable traded resource at potlatches and with neighboring Nations where it is used in preserving fruit, as a medicine and to lubricate tools (COSEWIC, 2011).

In the late 1800s the eulachon returns were considered by the Department of Fisheries to be vast and immense. Commercial fishing reported captures of 4.5 tonne in 1884. In 1887 observers were suggesting decreased eulachon in the Fraser River. While it appears to have rebounded in 1898 when the fishery peaked with a landing of 113 tonnes it has declined thereafter (Morin & Evan, 2022).

Consecutive years of variable low numbers returning to the river, resulted in the DFO closing the commercial and recreational fisheries in 1997 to allow for stock rebuilding. The populations have since collapsed even further (COSEWIC, 2011). Today, the Fraser River stock are recognized to be in a state of significant decline around 99% below pre-colonial levels, with a spawning biomass now under 10 tonnes. Pre-colonial estimates suggest spawning biomass runs of 1000-2000 tonne were the baseline (Morin & Evan, 2022). The species was designated as ‘endangered’ under the *Species at Risk Act* in May 2011.

As a major forage fish for the sturgeon, their decline has likely catalyzed the decline of the sturgeon (Morin & Evan, 2022).

One of the challenges in managing the stock is limited data availability on ecosystem constraints, and the high costs of acquiring further detailed data, on which to assess the stock’s status and manage a recovery.

Identified threats include dredging in river, pollution and impacts from forestry. Changes in the marine survival may also be contributing to the collapse of populations through environmental changes influencing predator-prey relationships and impacts of being caught as bycatch by trawlers (COSEWIC, 2011).

Surf Smelt (*Hypomesus pretiosus*)

Surf smelt are small (up to 22cm) schooling fish that utilize coastal estuaries as habitat. When 1-2 years old they spawn in the shallows along sandy and fine gravel beaches. Eggs incubate 2-15cm under the sandy substrate in these areas. They feed on a variety of zoobenthos and zooplankton like amphipods, copepods, worms, and fish eggs. Smelt form important prey for larger fish, birds, and mammals in the aquatic food web.

Smelt were an important food source for First Nations people around the Fraser River who dried them for winter food. Their abundance was such that they could be harvested by beach seine netting. As late as 1918 the smelt remained so abundant that they could be "raked ashore in large quantities with a garden rake" (Morin & Evan, 2022).

The coastwide commercial catches peaked in 1904 at more than 230 tonnes (Therriault, McDiarmid, Wulff, & Hay, 2002) and in 1911 in Burrard Inlet at 114 tonnes (Morin & Evan, 2022). The cause of decline has been attributed to initially increased fishing pressure, then habitat loss associated with pollution from population growth and industrialization (oil refineries and mills).

Today, a small commercial (rarely >10 tonne) and recreational fishery operates in Burrard Inlet, with a closed season over the peak spawning period. The smelt stock appears to be at greatly reduced biomass from historic levels (Morin & Evan, 2022).

White Sturgeon (*Acipenser transmontanus*)

White sturgeon is a very long-lived species that can slowly grow to nearly 6 meters in length and 800kg in weight. They inhabit the Lower Fraser River mainstem, tributaries and lakes below Hells Gate. The fish are slow to reach sexual maturity with males spawning at around 15 years of age and females at age 20 participating the broadcast spawning events. The females' eggs (ova) take up to 2.5 years to develop, with the interval between spawning event of 4 to 11 years.

Sturgeon are carnivorous. Juveniles eat amphipods, mysid shrimp, small fish like eulachons, sculpins, and sticklebacks.

Sturgeon was very abundant in the lower Fraser River and the mouth prior to colonial contact and formed a very important part of First Nations subsistence as they were available year-round. Early colonial reports document them purchasing sturgeon from First Nations fishers. A commercial fishery grew rapidly as colonial appetite for the fish boomed.

In 1884, 136,363kg of sturgeon was packed for export with a further 4545kg for local consumption. By 1898 Lower Fraser River catches had increased to peak around 500,000kg however it appears catches declined rapidly after then, to the point that when a large individual fish was caught in 1930 it was considered exceptional. Some areas like Burrard Inlet where sturgeon was historically captured are now considered locally extinct. A combination of overfishing, habitat damage and reduction of critical prey species, eulachon, are considered to have contributed to the current population now likely orders of magnitude lower than that which was the subject of First Nations fishing pre-colonial arrive (Morin & Evan, 2022).

From 1984 until the present the fishery for sturgeon has been strictly catch and release only.

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the species as threatened in 2012.

A monitoring and assessment program based on mark-recapture data and models has determined that populations of 7–55-year-old fish are reported to have declined by 25% since 2006 to a 2019 estimate of 44,809 fish. The estimated abundance of juvenile (Fork length 60-99cm, aged 7-12) has declined by more than 70% from 2004-2019. Fish 100-159cm (aged 13-22-sub-adult) have declined by 51.3% since 2009[61].

Growth rates from 2016-2019 appear to have reduced by 31% compared to 2010-2012.

The catch per unit effort of the Albion Test fishery has shown steady annual declines since 2000, particularly in fish under 100cm in length, implying less and less juvenile fish are entering the fishery (Challenger, et al., 2021).

Threats identified to the fishery include historic gravel extraction from the river, bycatch from set nets in the Food, Social and Ceremonial First Nations fishery, loss of access to habitat due to tidal floodgates and dykes, declining food availability of chum salmon and eulachon, siltation of spawning areas, changes in water temperature and flow through spawning, rearing and overwintering areas (Canadian Science Advisory Secretariat, 2021).

It is considered critical that harm needs to be reduced below current levels to achieve sustainability in this species.

Bull trout (*Salvelinus confluentus*)

Bull trout live in the lakes and undertake migration to the estuary and adjacent coast of the Fraser River catchment and south coast of British Columbia. They are a slow growing and late maturing species requiring cold pristine waters.

Government reports indicate they have declined in size and abundance in recent decades (Hagen & Decker, 2011). They are not subject to a commercial fishery but are captured by recreational anglers in a catch and release fishery. The species has been listed under the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species as vulnerable and the Fraser Basin population is designated as of 'special concern' by the Committee on the Status of Endangered Wildlife in Canada[62].

Bull trout are vulnerable to habitat degradation, fragmentation of river networks by blockages to passage (e.g dams)

Spiny dogfish (*Squalus acanthias*) North pacific spiny dogfish (*Squalus suckleyi*)

Spiny dogfish are slow growing, long lived, low fecundity sharks that inhabit the Strait of Georgia. They were fished from the 1800s through to the Second World War when effort expanded for their liver oil to provide Vitamin A prior to synthetic Vitamin A production. Now only a small quota directed fishery operates. The stock abundance is uncertain due to sparse data, some of which suggest marked declines (~75%) in the southern part of the Strait of Georgia from 1987-1991 and commercial longline catch per unit effort calculations suggests 44% declines between 1980-2008 (COSEWIC, 2011), While other studies suggest slight stock increases through some of the same period through to 2005 (King & McFarlane, 2009).

The IUCN has assessed the population as "vulnerable".

[61] https://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2021/2021_011-eng.html

[62] https://www.sararegistry.gc.ca/virtual_sara/files/cosewic/sr_omble_tete_plat_bull_trout_1113_e.pdf

Pacific herring (*Clupea pallasi*)

Pacific herring are the most abundant forage fish on the west coast of Canada. They are relatively short-lived and mature reproductively at 2-5 years of age. Massive annual spawning events turn the shallow inshore waters milky as eggs are laid and fertilized on weedy substrates along the water's edge. This location of spawning in shallow water makes them particularly vulnerable to inshore pollutant exposure. It is this annual recruitment, determined largely by the survival of the earliest life stages, which largely determines the annual abundance.

Herring have been and remain an important First Nations food source to many groups.

In 1881 colonial settlers introduced dynamite fishing methods on a large scale to capture an estimated 75 tonne of herring which were being delivered to a floating rendering plant to manufacture fish oil in Burrard Inlet. The herring meal was dumped into the bay. The commercial fishery developed further in adjacent waters from 1887 with catches increasing from 500 tonnes in 1900 to 35,000 tonnes in 1927. The reduction industry turning herring into fish meal and fish oil further developed from 1924. Catches continued to expand to 77,000 tonnes in 1964[63]. All five of the major stocks collapsed in the late 1960s, attributed to combination of unfavorable environmental conditions for recruitment and overfishing of a low spawning biomass. They recovered rapidly by the mid-1970s after a four-year fishery closure (Schweigert, Boldt, Flostran, & Cleary, 2010).

The stock biomass appears to be influenced by complex environmental conditions in terms of predators (including fishing), food availability, habitat, and pollution. Herring recruitment to the spawning population and subsequent survival has long been negatively correlated to sea surface temperature (Ware, 1991).

From 1972, some of the fishery targets spawning fish for their roe (eggs), with the bodies of these fish used for fish meal and fish oil production.

Several of the populations declined While under quota management from 1986 and failed to recover suggesting that ecosystem factors such as a lack of food supply, or excessive predation were limiting the recovery even with annual fishing closures in place.

The size for age declined between 1990-2010 suggesting potentially reduced food supply related to changed environmental conditions and may also be a consequence of other factors such as exposure to PAHs (Laurel, et al., 2019). The Strait of Georgia population remained above the biomass limit reference point, suggesting it was more stable than others up to 2010 and remained the subject of a quota fishery set at around 20% of the estimated stock biomass.

The Strait of Georgia is the last of the five stocks that has not completely collapsed today, however the recent trend suggests an estimated 60% decline in biomass from 2017-2020[64], but has remained open to fishing under the quota system. DFO dropped the harvest rate to 10% of the estimated stock biomass in response to data indicating stock declines in late 2021.

There is also a lack of Canadian data on contaminants and herring.

Data from Puget Sound to the south of the Fraser River coast suggests that sea surface microlayer contamination from complex mixtures of polycyclic aromatic hydrocarbons, pesticides and metals

[63] https://waves-vagues.dfo-mpo.gc.ca/Library/228283.pdf

[64] https://static1.squarespace.com/static/5ceed4a82de8d3000179e32f/t/6101b2c6953eff27826e5ac7/1627501254989/CHI+Herring+Report+2019.pdf

adjacent urban bays was associated with a more than 50% reduction in egg hatching and increased chromosomal aberrations in developing sand sole (*Psettichthys melanostictus*) embryos, compared to a rural reference bay (Hardy, et al., 1987) (Hardy, et al., 1987). Given herring spawn along the inshore, they appear at high risk of exposure to pollutants from land-based sources.

Pollution may be implicated in the decline. In the stocks to the south which have collapsed within Puget Sound levels of PCBs and DDT are elevated (West, O'Neill, & Ylitalo, 2008). Elevated rates of skeletal deformity and mortality in developing embryos have been demonstrated in areas that are polluted by oil spills from residual toxicity of PAHs (Incardona, et al., 2012). The developmental toxicity to the hearts of developing fish irreversible reduces their fitness (Incardona, et al., 2015). Even years after the spills, toxicity to the heart is detectable in new embryos that develop in the affected areas. Increased disease rates (Hershberger, et al., 2002) are also described which may relate to acute, chronic and transgenerational immunotoxicity (Rehberger, Werner, Hitzfeld, Segner, & Vaumann, 2017) rendering populations more at risk of disease expression.

The effect of this decline of forage fish within the first feeding areas of salmon may contribute to their decline also as a knock-on effect.

Sardine (*Sardinops sagax*)

Sardines are small pelagic school forage fish that eat both phytoplankton and zooplankton. They live for up to 15 years and can grow to 41cm in length. The pacific sardine stock is common across the range from the coast of Baja California, Oregon into British Columbia, Canada and to Alaska.

First Nations people were reported to have spoken of the historical abundance of sardines in times well before the arrival of colonial settlers. Sardine stocks were not evident in the early years of colonial settlement (Forester & Forester, 1975).

However, they became abundant in early 1900s to the point they were considered a pest as they ‘gummed up’ salmon fishers nets and ‘smeared’ the herring nets and were not considered suitable for human consumption due to the high oil content affecting the flavor. The necessity of providing food to soldiers in World War I saw them canned, but the product did not remain popular after the war.

The Department of Marine and Fisheries in Ottawa subsequently permitted commercial scale catching of the sardine for the sole purpose of the reduction (rendering) industry, to produce commodities for use in stock feed and fertilizer. The fish oil produced became a sought-after commodity for use in manufacture of soaps, perfumes in addition to paints, varnishes and the manufacture of margarine and became a bulk commodity being shipped around the world (Kelly L. , 1927).

From mid-1920s to mid-1940s catches averaged 40,000T per year. The fishery collapsed in 1947 with sardines totally disappearing again from British Columbia waters. While initially this was attributed by some as just a classic case of overfishing (McFarlane & Beamish, 1998), mostly by the US fleet (Ware, 1999). It is now apparent that wider oceanic conditions were playing a major role, as there were synchronous stock collapses in Japan, California USA, and Chile (Lluch-belda, et al., 1989).

Canada’s Committee on the Status of Endangered Wildlife in Canada (COSEWIC) listed the Pacific sardine as a species of concern in 1987.

The sardines reappeared in 1992 off British Columbia after an absence of nearly 50 years. The stock appeared to continue increasing in the late 1990s in line with the Californian stocks which were being commercially fished. B.C. reopened a cautious trial fishery in 2003, however by 2013 catches again collapsed[65].

Analysis of oceanic drivers such as the Pacific Decadal Oscillation, changes in predation pressure from other species like mackerel combined with high exploitation rates (in US fishery) were considered explanations for the most recent decline (Zwolinski & Demer, 2012). The US Department of Commerce National Oceanic and Atmospheric Administration calculations suggested much lower realized exploitation rates were occurring, which places far greater emphasis on the oceanographic conditions being the root cause of the boom-and-bust cycles (Hill, et al., 2011).

The role of this collapse in forage fish productivity on the productivity of other fisheries like salmon requires further ecological inquiry.

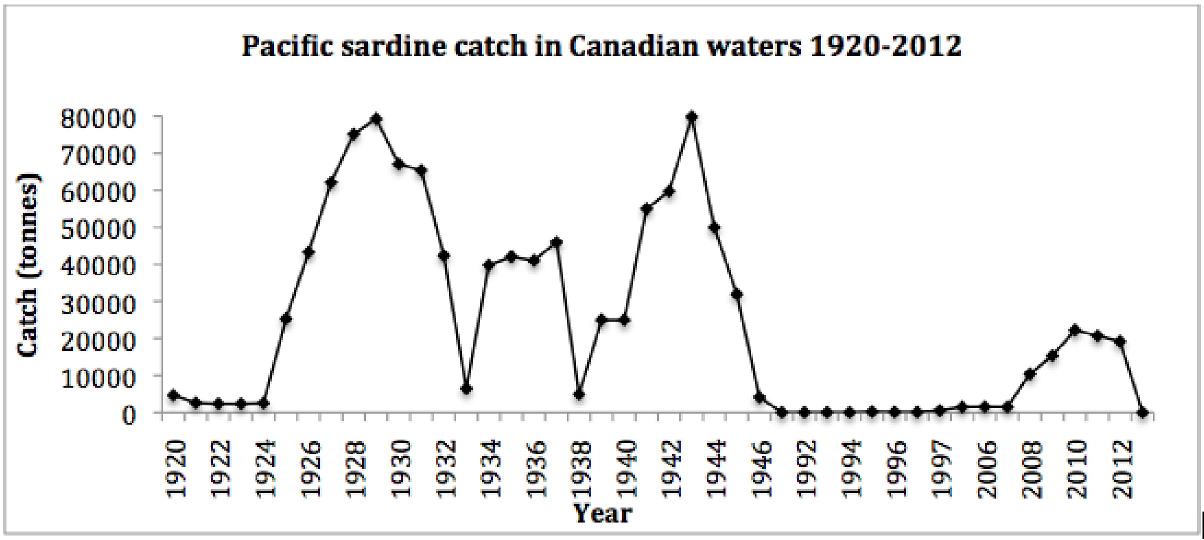

Figure 23: Trends of pacific sardine catch in Canadian waters (Data compiled from Hill et al 2011, DFO, 2013, McFarlane and Beamish 2001 as drawn in article by M. Warbanski[66] https://oceansciencehistory.files.wordpress.com/2014/01/screen-shot-2014-01-18-at-12-52-16-pm.png)

The Californian stock has again shown synchrony in declining with closure in B.C. in 2015 and severe restrictions in California through to the present day.

Examination of the dynamics of other sardine stocks such as the Indian Oil Sardine has raised the possibility that both oceanic factors and potential fishing pressure can contribute to stock collapse (Kripa, et al., 2018).

Other species

There have been dramatic declines in abundance of an array of other species since the colonial arrival. Formerly there were abundant crabs, clams and shellfish, waterfowl in flocks numbering tens of thousands, cod, flatfish, smelt which spawned in hundreds of tons on nearby beaches and banks, herring schools in the many millions and whales and porpoises (Morin & Evan, 2022).

As early as 1912 reports of pollution from oil refining activities were reported to be destroying clam populations in Burrard Inlet, adjacent the Fraser River delta. In 1912 commercial harvest of around

[65] https://oceansciencehistory.files.wordpress.com/2014/01/screen-shot-2014-01-18-at-12-52-16-pm.png
[66] https://oceansciencehistory.com/2014/01/18/the-rise-and-fall-of-pacific-sardine-in-west-coast-waters/

20,000kg was reported. By 1972 clam harvesting was prohibited in Burrard Inlet and Boundary Bay due to pollution and contamination (Morin & Evan, 2022).

Governance structures which manage the fishery and pollutant loads in the Fraser River

Fisheries in Canada are managed through both federal and provincial legislature outlined in Appendix 1. There is overlap of responsibilities in some areas. The fisheries remain a "common property resource belonging to all the people of Canada."

In 1937 the Government considered that commercial fishing pressures by USA and Canadian fishers had contributed substantially to the decline of sockeye salmon. At that time, the International Sockeye Salmon Treaty was ratified by Canada and USA to create the International Pacific Fisheries Commission. Canada agreed to make the entire Fraser River Basin available for restoration and propagation work with costs being shared between USA and Canada (Merriam, 1954).

However, successfully protecting water quality and aquatic habitat is a major challenge where the development pressure has been high, and where the management responses are fragmented at the watershed and ecosystem level. The control of land uses which generate the impacts are spread across many jurisdictions and decisions can be made that influence fisheries without due regard for those impacts.

The narrow view of resource-based management systems that seek to attain maximum short-term economic gains will require re-thinking to adopt ecosystem-based approaches that offer an opportunity to achieve successful protection.

The perception that the waste assimilative capacities of waters were a natural resource to be exploited, have led to regulatory control and administration acting to determine the distribution of waste discharge allocations (Keeling A. , 2004). Regulation has often been predicated on the ability of scientists to define pollution, analytical technologies to measure it, and the choices of critical bioassay endpoints which are used to assess toxicity risks from individual discharge sources. The political domain influences the creation of such policy as it is variably influenced by the opposing forces of pro-industry and environmentalists.

This type of regulatory outcome rapidly loses sight of the need to consider the productivity of aquatic ecosystems. River systems are highly exposed to 'death by a thousand cuts', whereby small incremental loads of pollutants ultimately harm their ecosystem function. Due to this complexity of interactions which sustain aquatic ecosystem productivity it is difficult to find a single species toxicity test endpoint which is adequate to serve as a prompt and cheap monitoring and compliance tool.

Biological toxicity test endpoints were used to assess pulp mill and wastewater plant effluent however they inadvertently build in the notion of acceptable losses of aquatic productivity to sustain a short-term economic benefit from a polluting industry. Even when effluent is compliant to a chosen endpoint, impacts still occur at more sensitive test endpoints, such as endocrine disruption, microbiome alteration or olfaction impairment. The ability of humans to manage their pollution impacts as development has modified landscapes has been hindered by scientific hubris which uncouples regulation from better use of the precautionary principle through over-simplification and failure to transparently acknowledge significant knowledge gaps.

The participation of the public is also a critical element that requires changes to consumer behavior to consider the impacts of the actions and choices made that impact aquatic ecosystems (Nener & Wernick, 1997). It also requires that the public recognize that even their small actions on stream sides can impact water quality and habitat. More than just an awareness of the problem is needed. Rather a complete renovation of value systems to place humans back within natural ecology, rather than continuing with the delusion that humanity is riding above all of nature. Such a shift could see the community actively engage in large numbers to invest time and capital into catchment restoration activities.

International commitments that influence pollution and fisheries

There are international obligations for the management of hazardous chemicals and wastes set out in the international chemical and waste conventions. As well as eliminating production and use of some of the world's most toxic substances, the Conventions provide the rules for trade in hazardous chemicals and waste; actively promote information exchange and technical capacity building; guide monitoring; and provide some financial assistance for developing countries or countries with economies in transition. They cover the key elements for the effective life-cycle management of hazardous chemicals. Canada is a signatory to the following conventions and agreements.

- *Stockholm Convention on Persistent Organic Pollutants* 2001
- *Basel Convention on Control of the Transboundary Movements of Hazardous Wastes and their disposal* 1989
- *Rotterdam Convention on Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade* 1998
- *Minamata Convention on Mercury* 2013
- *Paris Climate Agreement*

Combined, these conventions aim to protect human health and the environment from the adverse effects of toxic chemicals such as persistent organic pollutants (POPs), through the elimination of production, trade, use and release of POPs into the environment; from hazardous waste risks resulting from the generation, management, transboundary movements and disposal of hazardous and other wastes, taking into account the vulnerabilities of developing countries; and from anthropogenic emissions and releases of mercury and mercury compounds.

Canadian Fishery Governance is also influenced by the:

- *UN declaration on the Rights of Indigenous Peoples*

Changes to the *Fisheries Act* in 2018 sought to formalize consideration of Indigenous knowledge in decision-making.

- *Pacific Salmon Treaty 2019-2028*[67]

Federal Governance influencing pollutant load and fisheries in the Fraser River

The *Constitution Act, 1867* provides federal powers for conservation of fish stocks, maintenance, and preservation of the fishery as a whole, including its economic value. Several court cases from as early

[67] https://www.pac.dfo-mpo.gc.ca/fm-gp/salmon-saumon/pst-tsp/index-eng.html

as 1882 highlighted that the focus for the federal Government was to be on protecting and preserving the resource to prevent injurious exploitation of the resource[68], [69],.[70].

The Department of Fisheries and Oceans (DFO) have powers under the *Fisheries Act* to manage and regulate fisheries in Canada, including through the issuing licences and leases for fisheries (including aquaculture) or fishing. The *Fisheries Act p*rovides the basis for environmental protection of fish and fish habitat from destruction, harmful alteration, and disruption by "means other than fishing"[71] and by the general and specific prohibitions on depositing pollutants in Canadian fisheries waters[72]. It provides the basis for protection of fish and fish habitat. Fish habitat is broadly defined as "spawning grounds and nursery, rearing, food supply and migration areas on which fish depend directly or indirectly in order to carry out their life processes."[73]

Aquaculture Activities Regulations cover licensing, environmental management, biofouling, reporting of pests and disease and deposition of a deleterious substances such as fish medicine, and parasite treatments into waters.

First Nations treaty rights were recognized and affirmed in the *Constitution Act, 1982.* The right to fish for food, social and ceremonial purposes was recognized in 1990 within the Fraser River salmon fishery[74]. First Nations people are also supported to operate in the commercial fishery under separate allocations. First Nations must be consulted directly and in a timely fashion, prior to implementing planned conservation measures.

The full scope of First Nations rights and title in relation to the Fraser River salmon are still being explored on a group-by-group basis with court hearings taking place with a range of groups. Nonetheless, the federal Government maintains the overall control of administering management plans for the fishery. The federal Government manage based on the following order of priorities:

1) Conservation
2) First Nations fishing
3) Non-First Nations commercial fishing
4) Non-First Nations sports fishing[75]

The DFO co-operates with the provincial British Columbia Ministry of Environment and Climate Change Strategy to direct local government to improve the protection of fish and fish habitat through establishing directives to protect riparian areas of all designated streams, creeks, rivers, ditches, ponds, wetlands that are connected to a body of water which provides fish habitat under the *Riparian Areas Regulation,* where development is proposed.

BREAKOUT BOX *

Developments covered under *Riparian Areas Regulation*

---

[68] *The Queen v. Robertson,* [1882], 6SCR 52, paras.120-21.
[69] *Interprovincial Co-Operatives Ltd. v The Queen*, [1976] 1 SCR 477, p.495.
[70] *Ward v. Canada (Attorney-General),* [2002] 1 SCR 569 para 40. and 43.
[71] *Fisheries Act,* RSC 1985, c. F- 14, s. 32
[72] *Fisheries Act,* RSC 1985, c. F-14, s. 36
[73] *Fisheries Act*, RSC 1985, c. F-14, s.34
[74] *R. v. Sparrow* [1990] 1 SCR 1075, para 78.
[75] *Jack v. The Queen, (1980) 1 SCR 294, para. 313.*

Removal, alteration, disruption, or destruction of vegetation; disturbance of soils; construction or erection of buildings and structures; creation of non-structural impervious or semi-impervious surfaces; flood protection works; construction of roads, trails, docks, wharves, and bridges; provision and maintenance of sewer and water services; development of drainage systems; development of utility corridors; and subdivision as defined in section 872 of the *Local Government Act.*

The *Riparian Areas Regulation* does not apply to private lands where agriculture, mining, hydroelectric, forestry, federal and First Nations reserve lands, parks and parkland and other permanent structures like roads.

CLOSE BREAKOUT BOX*

Management of marine pollution and protection of the environment are also regulated by both federal and provincial jurisdictions. The *Fisheries Act* has general and specific prohibitions on depositing pollutants in waters of Canadian fisheries. Section 36 prohibits persons, unless authorized by regulation, from depositing or permitting the deposit of deleterious substances of any type "in water frequented by fish or in any place under any conditions where the deleterious substance or any other deleterious substance that results from the deposit of the deleterious substance may enter any such water."[76]

Provincial Governance influencing pollutant load and fisheries in the Fraser River

In 2007 a collaboration of federal Government (Environment and Climate Change Canada), the Province of British Columbia (B.C. Ministry of Environment), local Government and NGO's including Wetland Stewardship Partnership, Real Estate Foundation of British Columbia, Canadian Wildlife Service, BC Nature, Ducks Unlimited Canada and Grasslands Conservation Council of British Columbia supported the development of a Green Bylaws Toolkit for conserving sensitive ecosystems and green infrastructure which is now on its 3rd edition updated in 2021 (Environmental Law Clinic, University of Victoria, Faculty of Law, 2021).

The toolkit provides planners within local government and the public with tools to protect green infrastructure and ecosystem health to improve outcomes of land development. Legislation, guidelines, best practices, and bylaws are brought together to help communities towards sustainable development in B.C. The document includes case studies to demonstrate the practical application of legislation that highlight use of constructed wetlands, restoration of creeks, riparian areas and shorelines and habitat connectivity projects. This type of toolkit, with local adaptation to relevant regulation, likely has utility to be applied in other catchments around the world.

A summary of relevant legislation is in Appendix 1.

Have the Governance structures protected the fishery productivity of the Fraser River?

Unfortunately, the governance of the Fraser River fisheries and the management of land-use activities in the catchment have not proven sufficient to protect fisheries from significant declines. Investment of millions of dollars in science and monitoring has generated substantial volumes of knowledge, particularly on Pacific salmon. Many individual contributory causes have been described. Governance structures have attempted to implement these many learnings within a landscape of many competing

[76] *Fisheries Act*, RSC 1985, c. F-14, s.36

priorities and an overarching drive for economic development. It is certain that scientific knowledge alone, has been insufficient to drive changes to Governance, and changes to the behaviors of Canadian people sufficiently to realize the recovery of fisheries.

The technocratic governance approach taken is unable to correct for the prevailing economic system that promotes development and expanded consumption, nor does it seek to shift societal values to better align with nature. These fundamental deficiencies severely limit the ability of technocratic approaches to pollution control to resolve the multitude of pollution issues and facilitate aquatic ecosystem recovery.

Why has Governance failed to deliver salmon recovery?

Lack of prioritization within the economic system

From the moment the foundations of the colonial economic system were imposed upon British Columbia it has been fueled by expanded human population, increased exploitation of natural resources, expanded industrial activity accelerated by technological advancement powered by energy from combustion of fossil fuels and petrochemical innovations, and increased consumerism. These activities all inherently contribute to an expanded pollution footprint.

The recognition of the adverse effects of these activities and products of industrialization have consistently lagged their creation and mass release into the environment. Regulatory and industry responses to capture, treat or cease the generation of pollutants have lagged decades behind the early warnings. The primacy of seeking industrial economic growth directly conflicted with placing environmental protection and restoration as a paramount priority. Hence even when science described hazards to fisheries and regulation was drafted to correct the situation, implementation was incomplete. This was particularly the case were rigorous regulatory compliance to cause substantial economic loss to the industry involved. Consequently, sustained degradation of air, soil and water quality continues.

While there is some laudable intent within many areas of legislation to control pollutants and protect salmon and their habitats from adverse impacts, the actual protection provided is dramatically reduced by having exclusion clauses for many activities. Standards have improved for new developments, however the high cost of renovating inadequate major infrastructure for storm and sewage sustains legacy impacts on water quality.

Reflecting on the difference between the booming salmon fishery to the north in Bristol Bay Alaska and the demise of British Columbia's Fraser River salmon, the difference in human population, catchment degradation and industrial development within each catchment are striking (O'Neal & Woody, 2011).

BREAKOUT BOX OPEN*

Population, commerce, development and the individual

The abundance of wild salmon appears related to both the choices made by individual people and the total number of people. In this context it is perhaps only a desirable illusion that Fraser River salmon can be restored without massive changes to the catchment's (and planet's) human population number and to the consumptive lifestyles that have been normalized for many industrialized economies including Canada (Lackey, Lach, & Duncan, 2006).

Should society continue to expand population, development, consumption, fossil fuel extraction, petrochemical and plastic production, and industrial agriculture then, whether knowingly or not, it has decided to not seek a return to ecological sustainability. This solidifies the likely outcome of further declines in fisheries, even if many substantive restoration efforts are in play and millions are expended on improvements in fishery management science.

It is entirely unclear that at a country or global level people are willing to sacrifice their desire for more consumptive lifestyles, to support fishery recovery, as it would require them to undertake a wholesale adjustment to what have become core values of economic expansionist modern society. Society would have to accept that we cannot have it all and that the rules of commerce need to change to reflect the limited natural resources (Lackey, Lach, & Duncan, 2006).

The Salmon 2100 project (Lackey, Lach, & Duncan, 2006) identified four core policy drivers that they considered the basis to declines in US Pacific northwest salmon populations. Hence any serious effort to recover salmon in the Pacific Northwest must consider these:

1) Rules of commerce: increased globalization, economic efficiency borne of free trade ideologies do not consider the externality impacts on ecosystems in the race to least cost production. Extending the affluence of the wealthy has corresponding ecological consequences. The location of the ecological consequences may be a policy choice.
2) Increasing scarcity of key natural resources: the competition for high quality water is continuing to rise with rising population, expanded agriculture demand and greater climatic variability. The development of land continues at pace transforming evermore scarce natural resources. Expecting a reversal of such trends to aid recovery of salmon appears unlikely.
3) Regional human population levels: substantial further increases in human population are anticipated in the Pacific Northwest. Such population growth and its consumptive demands represent profound barriers to recovering salmon populations.
4) Individual and collective preferences: salmon recovery competes amongst many personal priorities like the price of power and food, cheaper clothing, restaurants. Some of these are mutually exclusive preferences, which may not support the required substantive action to recover salmon.

"*If we only continue to spend billions of dollars on quick-fix efforts to restore wild salmon runs, then in most cases these efforts will be only marginally successful. The billions spent on salmon recovery might be considered "guilt money"- modern-day indulgences- a tax society and individuals willingly bear to alleviate their collective and individual remorse. It is money spent on activities not likely to achieve recovery of wild salmon, but it helps people feel better as they continue the behaviors and choices that preclude the recovery of wild salmon."* (Lackey, Saving wild salmon: a 165 year policy conundrum, 2013)

Professor Robert T. Lackey, Department of Fisheries and Wildlife, Oregon State University

CLOSE BREAKOUT BOX

Competing priorities: development vs environment

There are many significant policy tensions for the DFO to manage such as the clearly competing priorities to maintain strong economic growth through supporting commercial fisheries and aquaculture production, while promoting a clean and healthy environment and the conservation of wild salmon.

To alleviate some of this tension the Cohen Commission recommended the Government of Canada remove the Department of Fisheries and Oceans' mandate to promote salmon farming as an industry and farmed salmon as a product, and re-stated that the conservation of the wild fishery was paramount priority which has overseen many Fraser River salmon fishery closures (Cohen B. , 2012).

Confusion of regulatory responsibilities

The Cohen Commission identified that the activity of monitoring of contaminants and their effects on salmon was not clearly held by DFO or Environment and Climate Change Canada, leading to gaps in diffuse source contaminant monitoring and research.

Lack of funding

The ability to appreciate the role played by contaminants on declining fisheries is reliant on firstly monitoring for the presence of various contaminants and subsequently on understanding their toxicological interactions and ecological effects. The Cohen Commission noted many contaminants were not monitored at all. While regular monitoring was recommended for emerging contaminants of concern and endocrine disrupting substances, shifting funding priorities contributed to the closure of DFO's Marine Environmental Quality section at the Institute of Ocean Sciences, leading to the loss of significant expertise and research capacity.

The migratory and multi-stage nature of salmon make studying the impacts of the myriad of contaminant mixture exposures on their life extremely difficult to study. This limits scientist's ability to generate data of sufficient certainty to inform regulatory processes which are reluctant to restrict a chemical that is already in use without such scientific certainty demonstrating harm (Ross, et al., 2013). The Cohen Commission recommended expanded monitoring of effluents from pulp mills, wastewater treatment plants and mines to consider effects on salmon, including endocrine effects. The commissioner also recommended that the province authorities perform a public education campaign to reduce toxicants like pharmaceuticals and personal care products in wastewater. He also recommended a regulatory strategy to limit impact of wastewater biosolids on fisheries resources (Cohen B. , 2012).

Inadequate licence conditions and compliance

Waste Management Permit specifications for effluents can allow release of harmful levels of substances to receiving waterways. The Cohen Commission noted the risk of harm to salmon from effluents from pulp and paper, metal mining and municipal wastewater were not being assessed. Neither DFO nor Health Canada were monitoring or researching the impacts of municipal wastewater on salmon. The new *Wastewater Systems Effluent Regulations* (WSER) came into force in 2012. These were an improvement and set baseline quality standards for secondary wastewater treatment including prohibiting release of effluent that was acutely lethal to rainbow trout. Owner/operators of wastewater systems were given 2 years to apply for a transitional authorization to exceed the WSER effluent quality limits. Across all of Canada, authorizations were issued to 65 systems with expiry in 2020, 2030, 2040 depending on risk criteria in the regulations.

OPEN BREAKOUT BOX**

2016 Status of Canada's Wastewater Systems Effluent Compliance

"*By the end of 2016, 1,737 wastewater systems out of an estimated 2,314 had submitted an identification report under the WSER. The majority (89%) of wastewater systems are owned by municipalities or other local governments. Lagoons make up more than half of the wastewater systems in Canada (56%), mechanical systems make up around a third (34%) and the remaining systems (10%) have no treatment. Of the 1,737 systems that submitted identification reports, 1,377 submitted all required monitoring reports, with 360 systems failing to submit one or more monitoring report. A total of 1,169 systems did not report any exceedances of the effluent quality limits, while 350 systems* *reported at least one exceedance. A total of 491 systems tested for acute lethality with 406 systems reporting no failures and 85 systems reporting an acute lethality test failure. A total volume of 5.2 billion m3 of effluent was discharged from a final discharge point for the 2016 calendar year. Of this total, 3.4 billion m3 (66%) met the WSER effluent quality limits, 1.7 billion m3 (33%) was undertreated and did not meet the limits, and 0.076 billion m3 (1%) of the effluent discharged underwent no treatment. These volumes do not include releases from combined sewer overflows (CSO), sanitary sewer overflows, or any other discharges occurring at a point other than the final discharge point. In Canada, as of 2016, 269 systems had at least one CSO. A total reported volume of 0.12 billion m3 of effluent was released from CSOs in 2016*." (Environment and Climate Change Canada, 2019)

CLOSE BREAKOUT BOX**

Failure to safely regulate pesticides for sensitive fish endpoints.

The Cohen Commission identified the lack of record keeping of pesticide volumes impaired DFO's ability to determine the role they were playing on salmon declines, so recommended that users be required to report annually both the areas and amounts of pesticides used, with the data to be made public (Cohen B. , 2012). This work has been the purview of the province through its pesticide sales surveys.

Inadequate protection of riparian habitats

In 1997 British Columbia provincial legislation was failing to protect water quality from development impacts on all public and private lands including sediment mobilization and riparian vegetation loss. A strategic plan identified that unenforceable guidelines needed to be replaced by laws which can be enforced providing stronger protections and incentives for private and public landholders to achieve protection of water quality. While penalties for non-compliance are likely to be necessary, there should also be consideration given to providing financial incentives to developers/landholders who achieve protection/restoration of water quality (Nener & Wernick, 1997).

While the subsequently introduced *Riparian Areas Regulation 2006* appeared to offer robust protection for these areas, the Cohen Commission identified the need to fully implement compliance and effectiveness monitoring as failure of robust implementation appears to be contributing to poor outcomes.

A gap was also identified that the regulation only applies to new residential, commercial, and industrial development on land under local government jurisdiction, thereby excluding private lands. The *Water Act* applies in and around streams, but only below the highwater mark so not permits are required for work above that level by private landholders. The *Riparian Areas Regulation* only applies above the one-in-five-year flood level, which leaves a gap of unregulated riparian area (Cohen B. , 2012). Amendments were made in 2019. The new *Riparian Areas Protection Regulation (RAPR)* improved regulatory oversight, incorporated training requirements, and provided additional detail and rigor in application of regulatory standards[77]. The growing impacts of climate change altering severe weather frequency, may render historic flood modelling redundant, suggesting more amendments will be required to effectively protect the riparian areas.

Cumulative impacts to habitats

The Cohen Commission identified that the cumulative effects of habitat loss were not adequately managed by DFO as the project-by-project assessment process was missing the bigger picture (Cohen

[77] https://www2.gov.bc.ca/gov/content/environment/plants-animals-ecosystems/fish/aquatic-habitat-management/riparian-areas-regulation/amendments-to-the-riparian-areas-regulation

B. , 2012). Corrective actions proscribed were to fully implement the 1986 Habitat Policy, which would generate a net gain in salmon habitat through protection of existing habitat, restoring damaged habitat, and creating new habitat.

The commissioner also recommended DFO undertake research on the cumulative effects of all identified stressors and incorporate their consideration into management.

The Cohen Commission recommended the provincial *Water Act* continue to be modernized to regulate extraction of groundwater and increase reporting and monitoring of water use. As population and agriculture has expanded there has been substantial expansion on water extraction and demand, with regulation not keeping pace and not aligning with protection of fisheries.

Inadequate implementation of policies

The DFO Wild Salmon Policy first released in 2005 offered an evidence-based pathway to conserve and recover wild salmon. While it recommended an implementation plan be developed to deliver the plan, this did not manifest until 2018. Similarly, the 1986 Habitat Policy offered opportunities to assist restoration and protection of salmon habitat. The fishery has declined further during this ensuing period While implementation was lacking. Ensuring that funding is available to support implementation, then monitoring to examine the effectiveness of implementation offer opportunities to improve.

Steps towards restoring productivity

Shifting societal values

In 2017 led by New Zealand's First Nations Māori the Whanganui River in New Zealand (Kramm, 2020) was the first river in the world to be granted legal personhood status. Subsequently several have followed including the Klamath River, USA, the Amazon River in Brazil and rivers in Columbia, Bolivia, Bangladesh, Ecuador, and Panama. In 2022 Canada took its first step towards shifting the legal status of rivers to that of a person, when the Magpie River in Quebec was granted personhood. When a river becomes a person, then harm to the river becomes equivalent to harm to a person. The river can then take legal action against a polluter for example. Such a shift may not only offer greater legal protections but, could help symbolically re-establish a healthier relationship between Canadians and their waterways. A shift away from utilitarian resource-exploitation paradigms of thinking is desperately needed.

Shifting away from individualism and personal consumption towards community interdependence could support macro shifts in behavior with consequential benefits to fisheries. The escalation of consumption has been in lockstep with increasing fossil fuel extraction and subsequent pollution of air, soil and water and declining planetary biodiversity.

Incorporation of First Nations Knowledge in co-management

In recent years the federal Government's commitment to reconciliation from the United Nations Declaration on the Rights of Indigenous Peoples, has seen greater collaborative effort to engage with First Nations people. This has included seeking to include and apply their indigenous knowledge systems to assist in the protection and recovery of fisheries[78]. This has now been legislated in Canada under the *United Nations Declaration on the Rights of Indigenous Peoples Act.*

[78] https://www.pac.dfo-mpo.gc.ca/fm-gp/salmon-saumon/wsp-pss/ip-pmo/index-eng.html

Fisheries research outcomes have not always been promptly applied to policy formulation and management. The emerging process of co-production of fishery research offers prospects to improve the translation of research into management action with inclusive, respectful partnerships (Cooke, et al., 2020).

Reform to operationalize the precautionary principle in chemical regulation

Regulatory reform must acknowledge that the level of certainty demanded in relation to data for identification of the role of individual chemicals toxicity within complex mixtures is unachievable, at least in the short term. A shift to a more precautionary approach, to reduce or remove exposures is urgently warranted. In relation to salmon, "*contaminants present a clear and imminent danger, ripe for targeting by precautionary management decisions*" (Ross, et al., 2013).

Regulatory reform is needed to include assessment of more sensitive endpoints in chemical environmental risk assessments. Acute toxicity endpoints are typically uninformative about biologically important sub-lethal chronic, endocrine, or immunological effects which alter species resilience and survival.

The composition of agricultural chemical products, including excipients (sometimes also referred to as adjuvants, inert ingredients, or carrier compounds), should be made publicly available.

Require public reporting of spatial and temporal use of all agricultural chemicals

The lack of publicly available data on the types of agricultural chemical products and the volumes of use in catchments hinder field research from demonstrating cause and effect relationships.

Address pollutants at the source

Reliance upon water and sewage treatment facilities to remove contaminants is both expensive and ineffective as safe disposal destinations for contaminated sludge remain elusive. Presently British Columbia permits re-use of sludge into agricultural, forestry and land reclamation. These destinations simply re-distribute the toxic load of PFAS, PBDE's, microplastics, metals and other contaminants in the sludge back up the catchment, which then wash back into the river. Focus must shift to prevention at the source of pollution, requiring reassessment of whether many products can be used safely when considered from a whole of lifecycle perspective.

Shift to ecosystem-based fishery management

Applying ecosystem-based management for fisheries assembles a multi-disciplinary effort to control the impacts on the function, resilience and productivity of aquatic environments and their fisheries.

Contaminants threaten the ability of aquatic life to survive through changes to their environment such as temperature and new pathogen exposures as their resilience can be reduced. Toxic exposures can manifest through modifying behavior, altering predation risk, impairing reproduction, altering nutrition through modifying food webs, impacting metabolism and developing, impairing immune function and causing an energetic cost to aquatic organisms to name just some of the pathways which are understood (Ross, et al., 2013) (Couillard, Courtenay, & Macdonald, 2008). Additional adverse effect pathways are still being discovered like transgenerational epigenetic impacts.

Such influences must be included in new fishery ecosystem-based management approaches. As the climate emergency plays out globally the resilience of aquatic ecosystems will be increasingly stretched to breaking point as the growing footprint of water pollution will have already eaten away the natural resilience aquatic animals have. Redressing water pollution can assist aquatic ecosystems to cope with added climate change stress.

Restore wetlands and fishery connectivity

Wetland restoration and connectivity offers an opportunity to expand access for salmon to critical food and habitat resources in the lower Fraser River. Restored wetlands can also improve carbon sequestration and restore water filtration properties and groundwater recharge that can reduce pollutant loads entering the river.

Incentivize improvements to urban stormwater

Within urban environments much can be achieved by incentivizing the design with green engineering and implementation of expanded permeable surfaces (sponge city models) to reduce stormwater flows, both within new developments and retrofitted to existing landscapes.

Replace use of herbicides in urban areas with alternative non-toxic management methods (steam, mulch, additional plantings). Remove use of pesticides, including PFAS pesticides like fipronil and bifenthrin, which are found to contaminate stormwater flows from urban areas.

Incentivize mass transit infrastructure to reduce individual car use. Require alternative tire preservatives which do not break down into toxic byproducts that run-off with stormwater. Increased street sweeping may assist in collecting tyre particles prior to their movement into waterways.

Ensure all stormwater is directed through a constructed treatment wetland prior to discharge into a waterway.

Upgrade sewage treatment plants and individual septic systems

Upgrade all sewage treatment plants to tertiary treatment level which ensures that released effluent is non-toxic.

Where sewage treatment plants are unable to achieve non-toxic discharge, investigation to identify major contributing compounds should be mandated. After identification, mandatory reporting to the relevant industrial, agricultural, veterinary, or therapeutic regulator is required. In turn the regulator must act to remove contamination risk at the source.

Provide incentive to upgrade septic systems which are in areas of high risk for contaminating surface water quality.

Accelerate the separation of stormwater and sewage piping in Vancouver (current goal 2050[79]) to avoid overflows of the current combined infrastructure in high rainfall periods.

Incorporate toxicity-testing bioassays into discharge permits. Where toxicity is identified the facility should be required to eliminate the problem. Compliance audits should be performed without prior warning to the proponent.

[79] https://vancouver.ca/home-property-development/separating-sewage-from-rainwater.aspx#:~:text=In%20a%20combined%20sewer%20system,the%20sewage%20treatment%20plant%20together.

References

Addison, R., Ikonomou, M., & Simth, T. (2005). PCDD/F and PCB in harbour seals (Phoca vitulina) from British Columbia: response to exposure to pulp mill effluents. *Marine Environmental Research, 59*, 165-176. doi:10.1016/j.marenvres.2004.04.005

Alava, J., Lukyanova, O., Ross, P., & Shim, W. (. (2020). *Report of Working Group 21 on Emerging Topics in Marine Pollution.* Sidney: North Pacific Marine Science Organization (PICES).

Ashley, K. (2010, March 30-31). *Speaking for the Salmon: Summit on Fraser River Sockeye Salmon-Understanding Stock Declines and Prospects for the Future.* Retrieved from Simon Fraser University: https://www.sfu.ca/rem/CRMI/SpeakingfortheSalmon/FraserSockeyDeclinesandFuture.html

Attard, M., Venditti, J., & Church, M. (2014). Suspended sediment transport in Fraser River at Mission, British Columbia: New observations and comparison to historical records. *Canadian Water Resources Journal*, 1-16. doi:10.1080/07011784.2014.942105

Austin, A., & Deniseger, J. (1985). Periphyton community changes along a heavy metals gradient in a long narrow lake. *Environmental and Experimental Botany, 25*, 41-52. doi:10.1016/0098-8472(85)90047-4

Baker, M., Schindler, D., Holtgrieve, G., & St Louis, V. (2009). Bioaccumulation and transport of contaminants: migrating sockeye salmon as vectors of mercury. *Environmental Science and Technology, 43*(23), 8840-8846. doi:10.1021/es901798f

Baldwin, D., Spromberg, J., Collier, T., & Scholz, N. (2009). A fish of many scales: extrapolating sublethal pesticide exposures to the productivity of wild salmon populations. *Ecological Applications, 19*(8), 2004-2015.

Barisic, J., Cannon, S., & Quinn, B. (2019). Cumulative impact of anti-sea lice treatment (azamethiphos) on health status of Rainbow trout (Oncorhynchus mykiss, Walbaum 1792) in aquaculture. *Scientific Reports Nature, 9*, 16217. doi:10.1038/s41598-019-52636-1

Barrie, V., & Currie, R. (2000). Human impact on the sedimentary regime of the Fraser River Delta, Canada. *Journal of Coastal Research, 16*(3), 747-755.

Bass, A., Bateman, A., Connors, B., Staton, B., Rondeau, E., Mordecai, G., . . . Miller, K. (2022). Identification of infectious agents in early marine Chinook and Coho salmon associated with cohort survival. *FACETS, 7*, 742-773. doi:10.1139/facets2021-0102

Beamish, R., Neville, C., Sweeting, R., & Lange, K. (2012). The synchronous failure of juvenile pacific salmon and herring production in the Strait of Georgia in 2007 and the poor return of sockeye salmon to the Fraser River in 2009. *Marine and Coastal Fisheries, 4*(1), 403-414. doi:10.1080/19425120.2012.676607

Beamish, R., Neville, C., Sweeting, R., Jones, S., Ambers, N., Gordon, E., . . . McDonald, T. (2007). A proposed life history strategy for the salmon louse, Lepeophtheirus salmonis in the subarctic Pacific. *Aquaculture, 264*, 428-440. doi:10.1016/j.aquaculture.2006.12.039

Bellringer, C. (2016). *An audit of compliance and enforcement of the mining sector.* Victoria: Auditor General of British Columbia. Retrieved from https://www.bcauditor.com/sites/default/files/publications/reports/OAGBC%20Mining%20Report%20FINAL.pdf

Bender, M., Giebichenstein, J., Teisrud, R., Laurent, J., Reinardy, H., Laurel, B., & Nahrganh, J. (2021). Combined effects of crude oil exposure and warming on eggs and larvae of an arctic forage fish. *Scientific reports, 11*, 8410. doi:10.1038/s41598-021-87932-2

Blais, J., Schindler, D., Muir, D., Sharp, M., Donald, D., Lafreniere, M., . . . Strachan, W. (2001). Melting glaciers: a major source of persistent organochlorines to subalpine Bow Lake in Banff National Park, Canada. *AMBIO: A Journal of the Human Environment, 30*(7), 410-415. doi:10.1579/0044-7447-30.7.410

Boas, F. (1888, March). The Indians of British Columbia. *The Popular Science Monthly, 32*, p. 636.

Bohn, T., Gjelland, K., Serra-Llinares, R., Finstad, B., Primicerio, R., Nilsen, R., . . . Bjorn, P. (2020). Timing is everything: survival of Atlantic salmon Salmo salar post-smolts during events of high salmon lice densities. *Journal of Applied Ecology*, 1-12. doi:10.1111/1365-2664.13612

Bouwes, N., Weber, N., Jordan, C., Saunders, C., Tattam, I., Volk, C., & Wheaton, J. P. (2016). Ecosystem experiment reveals benefits of natural and simulated beaver dams to a threatened population of steelhead (Oncorrhynchus mykiss). *Scientific Reports, 6*, 28581. doi:10.1038/srep28581

Brewer, R., Sekela, M., Sylvestre, S., Tuominen, T., & Moyle, G. (1998). *Contaminants in bed sediments from 15 reaches of the Fraser River Basin.* Aquatic and Atmospheric Sciences Division. Vancouver: Environment Canada.

Brinkmann, M., Montgomery, D., Selinger, S., Miller, J., Stock, E., Alcaraz, A., . . . Wiseman, S. (2022). Acute toxicity of the tire rubber-derived chemical 6PDD-quinone to four fishes of commercial, cultural, and ecological importance. *Environmental Science & Technology Letters, 9*, 333-338. doi:10.1021/acs.estlett.2c00050

Brown, T., Haigh, N., & Johnson, D. (2018). Interannual variation of the toxic raphidophyte Heterosigma akashiwo in Departure Bay (Nanaimo): data from the harmful algae monitoring program 2001-2017. *Salish Sea Ecosystem Conference* (p. 91). Seattle: Western Washington University, Western CEDAR.

Burd, B., Lowe, C., Morales-Caselles, C., Noel, M., Ross, P., & Macdonald, T. (2019). Uptake and trophic changes in polybrominated diphenyl ethers in the benthic marine food chain in south western British Columbia, Canada. *FACETS, 4*, 20-51. doi:10.1139/facets-2018-0021

Burd, B., Macdonald, R., Johannessen, S., & van Roodselaar, A. (2008). Responses of subtidal benthos of the Strait of Georgia, British Columbia, Canada to ambient sediment conditions and natural and anthropogenic depositions. *Marine Environmental Research, 66*, S62-S79. doi:10.1016/j.marenvres.2008.08.009

Burridge, L., Weis, J., Cabello, F., Pizarro, J., & Bostick, K. (2010). Chemical use in salmon aquaculture: A review of current practices and possible environmental effects. *Aquaculture, 306*, 7-23. doi:10.1016/j.aquaculture.2010.05.020

Canadian Science Advisory Secretariat. (2021). *Recovery Potential Assessment for Lower Fraser River White Sturgeon 2020.* Ecosystems and Oceans Science. Fisheries and Oceans Canada.

Challenger, W., Nelson, T., Robichaud, D., English, K., Mochizuki, T., & Thibault, T. (2021). *Status of White Sturgeon in the Lower Fraser River in 2020.* Sidney: Fraser River Sturgeon

Conservation Society. Retrieved from https://www.frasersturgeon.com/wp-content/uploads/2021/10/Lower-Fraser-Sturgeon-M-and-A-2020-Report_20211024.pdf

Chibwe, L., Parrot, J., Shires, K., Khan, H., Clarence, S., Lavalle, C., . . . Rochman, C. (2021). A deep dive into the complex chemical mixture and toxicity of tire wear particle leachate in fathead minnow. *Environmental Toxicology, 00*(00), 1-10. doi:10.1002/etc.5140

Chisholm, B. (1986). *Reconstruction of prehistoric diet in British Columbia using stable-carbon isotopic analysis.* Department of Archaeology. Simon Fraser University.

Christensen, V., & Trites, A. (2011). *Predation on Fraser River Sockeye Salmon- Technical Report 8.* Vancouver: Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River.

Claxton, N. (2008). IISTÁ SĆIÁNEW, ISTÁ SXOLE: 'To FIsh as Formerly" the Douglas Treaties and the WSÁNEĆ Reef-Net Fisheries. In L. (. Simpson, *Lighting the Eighth Fire: The Liberation, Resurgence, and Protection of Indigenous Nations* (pp. 54-55). Winnipeg: Arbeiter Ring.

Clutesi, G. (1969). *Potlatch (2nd edition).* Victoria, BC: The Morriss Printing Company.

Cohen, B. (2011, mAY 9). Commission of Inquiry into the decline of sockeye salmon in the Fraser River- public hearings. 104. Vancouver, British Columbia.

Cohen, B. (2012). *Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River: The Uncertain Future of Fraser River Sockeye: Volume 1-The Sockeye Fishery.* Ottawa: Public Works and Government Services, Canada.

Cohen, B. (2012). *The uncertain future of Fraser River sockeye - Volume 2.* Ottawa: Minister of Public Works and Government Services Canada.

Cohen, B. (2012). *The Uncertain Future of Fraser River Sockeye-Volume 3-recommendations-summary-process.* Ottawa: Public Works and Government Services Canada.

Cole, D., & Chaikin, I. (1990). *An Iron Hand upon the People: The Law against the Potlatch on the Northwest Coast.* Vancouver and Toronto.

Collicutt, B., Juanes, F., & Dudas, S. (2019). Microplastics in juvenile Chinook salmon and their nearshore environments on the east coast of vancouver island. *Environmental Pollution, 244*, 135-142. doi:10.1016/j.envpol.2018.09.137

Cooke, S., Nguyen, V., Chapman, J., Reid, A., Landsman, S., Young, N., . . . Semeniuk, C. (2020). Knowledge co-production: A pathway to effective fisheries management, conservation, and governance. *Fisheries Magazine, 46*(2), 89-97. doi:10.1002/fsh.10512

COSEWIC. (2011). *COSEWIC assessment and status report on the Eulachon, Nass/ Skeena Rivers population, Central Pacific Coast population and the Fraser River population Thaleichthys pacificus in Canada.* Ottawa: Committee on the Status of Endangered Wildlife in Canada. Retrieved from https://www.sararegistry.gc.ca/virtual_sara/files/cosewic/sr_eulachon_0911_eng.pdf

COSEWIC. (2011). *COSEWIC assessment and status report on the North Pacific Spiny Dogfish Squalus suckleyi in Canada.* Ottawa: Environment Canada. Retrieved from https://publications.gc.ca/collections/collection_2012/ec/CW69-14-644-2012-eng.pdf

Couillard, C., Courtenay, S., & Macdonald, R. (2008). Chemical-environment interactions affecting the risk of impacts on aquatic organisms: A review with a Canadian perspective - interactions affecting vulnerability. *Environmental Reviews, 16*, 19-44. doi:10.1139/A07-008

Cousins, I., Johansson, J., Slater, M., Sha, B., & Scheringer, M. (2022). Outside the safe operating space of a new planetary boundary for Per- and Polyfluoroalkyl substances (PFAS). *Environmental Science & Technology*. doi:10.1021/acs.est.2c02765

Crossin, G., Hinch, S., Cooke, S., Welch, D., Patterson, D., Jones, S., . . . Farrell, A. (2008). Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration. *Canadian Journal of Zoology, 86*, 127-140. doi:10.1139/Z07-122

Davidson, S. (2018). *Potlatch as Pedagogy.* Winnipeg, Manitoba: Portage and Main.

Debruyn, A., Ikonomou, M., & Gobas, F. (2004). Magnification and toxicity of PCBs, PCDDs, and PCDFs in upriver-migrating Pacific Salmon. *Environmental Science & technology, 38*, 6217-6224. doi:10.1021/es049607w

Deguine, J.-P., Aubertot, J.-N., Flor, R., Lescourret, F., Wyckhuys, K., & Ratnadass, A. (2021). Intergated pest management: good intention, hard realities. A review. *Agronomy for Sustainable Development, 41*(38). doi:10.1007/s13593-021-00689-w

Deniseger, J., Erickson, L., Austin, A., Roch, M., & Clark, M. (1990). The effects of decreasing heavy metal concentrations on the biota of Buttle Lake, Vancouver Island, British Columbia. *Water Research, 24*(4), 403-416. doi:10.1016/0043-1354(90)90222-R

Desforges, J., Galbraith, M., & Ross, P. (2015). Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. *Archives of Environmental Contamination and Toxicology, 69*, 320-330. doi:10.1007/s00244-015-0172-5

Desforges, J., Galbraith, M., Dangerfield, N., & Ross, P. (2014). Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. *Marine Pollution Bulletin, 79*, 94-99. doi:10.1016/j.marpolbul.2013.12.035

Desforges, J.-P., Hall, A., McConnell, B., Rosing-Asvid, A., barber, J., Brownlow, A., . . . Dietz, R. (2018). Predicting global killer whale population collapse from PCB pollution. *Science, 361*, 1373-1376. doi:10.1126/science.aat1953

DFO. (2001). *Interior Fraser River Coho Salmon- DFO Scicence Stock Report D6-08.* Department of Fisheries and Oceans, Canada. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/345781.pdf

Di Cicco, E., Ferguson, H., Kaukinen, K., Schulze, A., Li, S., Tabata, A., . . . Miller, K. (2018). The same strain of Piscine orthoreovirus (PRV-1) is involved in the development of different, but related, diseases in Atlantic and Pacific Salmon in British Columbia. *FACETS, 3*, 599-641. doi:10.1139/facets-2018-0008

Dill, L. (2011). *Impacts of salmon farms on Fraser River sockeye salmon results of the Dill investigation. Cohen Commission Technical Report 5D.* Vancouver BC: Cohen Commission.

Dugdale, S., Malcolm, I., Kantola, K., & Hannah, D. (2018). Stream temperature under contrasting riparian forest cover: Understanding thermal dynamics and heat exchange processes. *Science of the Total Environment, 610-611*, 1375-1389. doi:10.1016/j.sciotenv.2017.08.198

Elliot, K., & Elliott, J. (2016). Origin of sulfur in diet drives spatial and temporal mercury trends in seabird eggs from Pacific Canada 1968-2015. *Environmental Science and Technology, 50*, 13380-13386. doi:10.1021/acs.est.6b05458

Enerman, S. (2021). *Bridging the gap: towards best international standards on mine waste safety in British Columbia.* Utah: BC Mining Law Reform and MiningWatch Canada.

Environment and Climate Change Canada. (2019). *Wastewater Systems Effluent Regulations- 2016 Status Report.* Gatineau: Environment and Climate Change Canada.

Environmental Law Clinic, University of Victoria, Faculty of Law. (2021). *Green Bylaws Toolkit for Protecting and Enhancing the natural Environment and Green Infrastructure.* The Wetland Stewardship Partnership. Retrieved from https://stewardshipcentrebc.ca/PDF_docs/GreenBylaws/GreenBylawsToolkit_3rdEdition_2021.pdf

Esenkulova, S., Suchy, K., Pawlowicz, R., Costa, M., & Pearsall, I. (2021). Harmful algae and oceanographic conditions in the Strait of Georgia, Canada based on citizen science monitoring. *frontiers in Marine Science, 8*, 725092. doi:10.3389/fmars.2021.725092

Ewald, G., Larsson, P., Linge, H., Okla, L., & Szarzi, N. (1998). Biotransport of organic pollutants to an inland Alaska Lake by migrating Sockeye salmon (Oncorhynchus nerka). *Arctic, 51*(1), 40-47.

Fabry, V., McClintock, J., Mathis, J., & Grebmeier, J. (2009). Ocean acidification at high latitudes: the bellwether. *Oceanography, 22*(4), 160-171.

Fairchild, W., Swansburg, E., Arsenault, J., & Brown, S. (1999). Does an association between pesticide use and subsequent declines in catch of Atlantic Salmon (Salmo salar) represent a case of endocrine disruption? *Environmental Health Perspectives, 105*(5), 349-357.

Finn, R., Chalifour, L., Gergel, S., Hinch, S., Scott, D., & Martin, T. (2021). Quantifying lost and inaccessible habitat for Pacific salmon in Canada's Lower Fraser River. *Ecosphere, 12*(7), e03646. doi:10.1002/ecs2.3646

Fisheries and Oceans Canada. (2022, January 19). *2021 Fraser River Stock Assessment and Fishery Summary: Coho and Chum Salmon.* Retrieved from https://frasersalmon.ca/wp-content/uploads/2021/12/2021-FR-CO-CM-Post-season-Review-for-FA-Salmon-Forum-2022-01-19.pdf

Ford, J., & Myers, R. (2008). A global assessment of salmon aquaculture impacts on wild salmonids. *PLoS ONE, 6*(2), e33. doi:10.1371/journal.pbio.0060033

Forester, J., & Forester, A. (1975). *Fishing: British Columbia's Commercial Fishing History.* Saanichton: Hancock House Publishers.

Forrester, C., Ketchen, K., & Wong, C. (1972). Mercury content of spiny dogfish (Squalus acanthias) in the Strait of Georgia, British Columbia. *Journal Fisheries Research Board of Canada, 29*(10), 1487-1493. doi:10.1139/f72-231

Gao, H., Zhou, J., Dong, S., & Kitazawa, D. (2022). Sustainability assessment of marine aquaculture considering nutrients inflow from the land in Kyushu area. *Water, 14*(943), w14060943. doi:10.3390/w14060943

Gewurtz, S., Backus, S., De Silva, A., Ahrens, L., Armellin, A., Evans, M., . . . al, e. (2013). Perfluoroalkyl acids in the Canadian environment: Multi-media assessment of current status and trends. *Environment International, 59*, 183-200. doi:10.1016/j.envint.2013.05.008

Gies, E., LeNoble, J., Noel, M., Etemadifar, A., Bishay, F., Hall, E., & Ross, P. (2018). Retention of microplastics in a major secondary wastewater treatment plan in Vancouver, Canada. *Marine Pollution Bulletin, 133*, 553-561. doi:10.1016/j.marpolbul.2018.06.006

Godwin, S., Bateman, A., Kuparinen, A., Johnson, R., Powell, J., Speck, K., & Hutchings, J. (2022). Salmon lice in the Pacific Ocean show evidence of evolved resistance to parasiticide treatment. *Scientific Reports, 12*, 4775. doi:10.1038/s41598-022-07464-1

Gottschall, N., Topp, E., Edwards, M., Russell, P., Payne, M., Kleywegt, S., . . . Lapen, D. (2010). Polybrominated diphenyl ethers, perfluorinated alkylated substances, and metals in tile drainage and groundwater following applications of municipal biosolids to agricultural fields. *Science of the Total Environment, 408*(4), 873-883. doi:10.1016/j.scitotenv.2009.10.063

Grant, S., & Pestal, G. (2009). *Certification Unit Profile: Fraser River Chum Salmon.* Vancouver: Department of Fisheries and Oceans. Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.492.4892&rep=rep1&type=pdf

Hagen, J., & Decker, S. (2011). *The status of bull trout in British Columbia: a synthesis of available distribution, abundance, trend, and threat information.* Ministry of Environment, Ecosystems Protection & Sustainability branch, Aquatic Conservation Science Section. Victoria: Province of British Columbia.

Hagen, M., Colodey, A., Knapp, W., & Samis, S. (1997). Environmental response to decreased dioxin and furan loadings from British Columbia coastal pulp mills. *Chemosphere, 34*(5-7), 1221-1229. doi:10.1016/s0045-6535(97)00420-7

Hall, K., & Schreier, H. (1996). Urbanization and agricultural intensification in the Lower Fraser River valley: Impacts on water use and quality. *GeoJournal, 40*(1-2), 135-146.

Hamilton, A., Laval, B., Petticrew, E., Albers, S., Allchin, M., Baldwin, S., . . . Vagle, S. (2020). Seasonal turbidity linked to physical dynamics in a deep lake following the catastrophic 2014 Mount Polley Mine tailings spill. *Water Resources Research, 56*(8), e2019WR025790. doi:10.1029/2019WR025790

Harding, T., Jaremovic, L., & Kosakosko, G. (1994). *Strategic review of fisheries resources, North Thompson Habitat Management Area, Fraser River Action Plan.* Vancouver, BC: Department of Fisheries and Oceans.

Hardy, J., Crecelius, E., Antrim, L., Broadhurst, V., Apts, C., Gurtisen, J., & Fortman, T. (1987). The sea-surface microlayer of puget sound: Part II. Concentrations of contaminants and relation to toxicity. *Marine Environmental Research, 23*(4), 251-271. doi:10.1016/0141-1136(87)90021-3

Hardy, J., Kiesser, S., Antrim, L., Stubin, A., Kocan, R., & Strand, J. (1987). The sea-surface microlayer of Puget Sound: part 1. Toxic effects on fish eggs and larvae. *Marine Environmental Research, 23*, 227-249.

Harris, D. (2001). *Fish Law and Colonialism: The Legal Capture of Salmon in British Columbia.* Toronto: University of Toronto Press.

Harris, K., Dangerfield, N., Woudneh, M., Brown, T., Verrin, S., & Ross, P. (2008). Partitioning of current-use and legacy pesticides in salmon habitat in British Columbia, Canada. *Environmental Toxicology and Chemistry, 27*(11), 2253-2262.

Hartman, G., Northcote, T., & Cederholm, C. (2013, Spring). Human numbers- the alpha factor affecting the future of wild salmon. *The Social Contract*, pp. 18-20. Retrieved from https://www.thesocialcontract.com/pdf/twentythree-three/tsc_23_3_hartman.pdf

Healey, M. (2011). The cumulative impacts of climate change on Fraser River sockeye salmon (Oncorhynchus nerka) and implications for management. *Canadian Journal of Fisheries and Aquatic Science, 68*, 718-737. doi:10.1139/F2011-010

Heintz, R. (2007). Chronic exposure to polynuclear aromatic hydrocarbons in natal habitats leads to decreased equilibrium size, growth and stability of pink salmon populations. *Integrated Environmental Assessment and Management, 3*(3), 351-363. doi:10.1002/ieam.5630030306

Hepler-Smith, E. (2019). Molecular Bureauracy: Toxicological Information and Environmental Protection. *Environmental History*, 534-560. doi:10.1093/envhis/emy134

Hershberger, P., Stick, K., Bui, B., Carroll, C., Fall, B., Mork, C., . . . Kocan, R. (2002). Incidence of Ichthyophonus hoferi in Puget Sound Fishes and its increase with age of Pacific Herring. *Journal of Aquatic Animal Health, 14*(1), 50-56. doi:10.1577/1548-8667(2002)014<0050:IOIHIP>2.0.CO;2

Hertzberg, P. (1983). *Mining and Pollution in B.C.* Victoria: University of Victoria.

Hill, K., Crone, P., Lo, N., Macewicz, B., Dorval, E., McDaniel, J., & Gu, Y. (2011). *Assessment of the Pacific sardine resource in 2011 for U.S. management in 2012.* National Oceanic and Atmospheric Administration, US Department of Commerce. La Jolla, California: National Marine Fisheries Service.

Hinch, S., & Martins, E. (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.* Vancouver: Cohen Commission Technical Report 9.

Incardona, J., Carls, M., Holland, L., Linbo, T., Baldwin, D., Myers, M., . . . Scholz, N. (2015). Very low embryonic crude oil exposures cause lasting cardiac defects in salmon and herring. *Scientific Reports, 5*, 13499. doi:10.1038/srep13499

Incardona, J., Vines, C., Anulacion, B., Baldwin, D., Day, H., French, B., . . . Scholz, N. (2012). Unexpectedly high mortality in Pacific herring embryos exposed to the 2007 Cosco Busan oil spill in San Francisco Bay. *PNAS, 109*(2), E51-E58. doi:10.1073/pnas.1108884109

International Pacific Salmon Fisheries Commission. (1964). *Annual Report-1963.* New Westminster.

Janicki, E. (2008). *Petroleum exploration history of British Columbia, Canada.* Victoria: British Columbia Ministry of Energy Mines and Petroleum Resources.

Johannessen, C., Helm, P., Lashuk, B., Yargeau, V., & Metcalfe, M. (2022). The tire wear compounds 6PDD-Quinone and 1,3-Diphenylguanidine in an urban watershed. *Archives of Environmental Contamination and Toxicology, 82*(2), 171-179. doi:10.1007/s00244-021-00878-4

Johannessen, D., & Ross, P. (2002). *Late-run Sockeye at risk: an overview of environmental contaminants in Fraser River salmon habitat.* Institute of Ocean Sciences. Sidney: Fisheries and Oceans Canada.

Johannessen, S., Macdonald, R., & Magnus Eek, K. (2005). Histoircal trends in mercury sedimentation and mixing in the Strait of Georgia, Canada. *Environmental Science and Technology, 39*, 4361-4368. doi:10.1021/es040535i

Johannessen, S., Macdonald, R., Burd, B., van Roodselaar, A., & Bertold, S. (2015). Local environmental conditions determine the footprint of municipal effluent in coastal waters: A case study in the Strait of Georgia, British Columbia. *Science of the Total Environment, 508*, 228-239. doi:10.1016/j.scitotenv.2014.11.096

Johannessen, S., Masson, D., & Macdonald, R. (2014). Oxygen in the deep Strait of Georgia, 1951-2009: The roles of mixing, deep-water renewal, and remineralization of organic carbon. *Limnology and Oceanography, 59*(1), 211-222. doi:10.4319/lo.2014.59.1.0211

Johnston, B., Seubert, J., & Kennedy, C. (1998). Biochemical effects of didecyldimethylammonium chloride (DDAC) exposure and osmoregulatory stress on juvenile coho salmon, Oncorhynchus kisutch. *Archives of Environmental Contamination and Toxicology, 34*, 275-279. doi:10.1007/s002449900318

Keeling, A. (2004, July). The effluent society: water pollution and environmental politics in British Columbia, 1889-1980. *Thesis in partial fulfillment of the requirements for the degree of Doctor of Philosophy*. The University of British Columbia.

Keeling, A. (2005, September 22). Urban waste sinks as a natural resource: the case of the Fraser River. *Urban History Review*.

Kelly, B., Ikonomou, M., Higgs, D., Oakes, J., & Dubetz, C. (2008). mercury and other trace elements in farmed and wild salmon from British Columbia, Canada. *Environmental Toxicology and Chemistry, 27*(6), 1361-1370. doi:10.1897/07-527 ·

Kelly, L. (1927, January 1). Humble pilchard becomes a blueblood- the amazing story of the growth of a new industry in British Columbia. *Macleans-Canada's National magazine*, pp. 14-15.

Ketchen, K. (1986). *The Spiny Dogfish (Squalus acanthias) in the Northeast pacific and a History of its Utilization.* Nanaimo: Department of Fisheries and Oceans.

Khangaonkar, T., Nugraha, A., Xu, W., Long, W., Bianucci, L., Ahmed, A., . . . Pelletier, G. (2018). Analysis of hypoxia and sensitivity to nutrient pollution in Salish Sea. *Journal of Geophysical Research: Oceans, 123*, 4735-4761. doi:10.1029/2017JC013650

Kibenge, M., Iwamoto, T., Wang, Y., Morton, A., Godoy, M., & Kibenge, F. (2013). Whole-genome analysis of piscine reovirus (PRV) shows PRV represents a new genus in family Reoviridae and its genome segment S1 sequences group it into two separate sub-genotypes. *Virology Journal, 10*, 230. doi:10.1186/1743-422X-10-230

Kibenge, M., Wang, Y., Gayeski, N., Morton, A., Beardslee, K., McMillan, B., & Kibenge, F. (2019). Piscine orthoreovirus sequences in escaped farmed Atlantic salmon in Washington and British Columbia. *Virology Journal*, 16:41. doi:10.1186/s12985-019-1148-2

King, J., & McFarlane, G. (2009). Trends in abundance of spiny dogfish in the Strait of Georgia, 1980-2005. In V. Gallucci, G. McFarlane, & G. Bargmann (Eds.), *Biology and Management of Dogfish Sharks* (pp. 89-100). American Fisheries Society.

Kramm, M. (2020). When a River Becomes a Person. *Journal of Human Development and Capabilities, 21*(4), 307-319. doi:10.1080/19452829.2020.1801610

Kripa, V., Mohamed, K., Said Koya, K., Jeyabaskaran, R., Prema, D., Padua, S., . . . Vishnu, P. (2018). Overfishing and climate drives changes in biology and recruitment of the Indian Oil Sardine Sardinella longiceps in Southeastern Arabian Sea. *frontiers in Marine Science, 5*, 443. doi:10.3389/fmars.2018.00443

Krkosek, M., Connors, B., Ford, H., Peacock, S., Mages, P., Ford, J., . . . Lewis, M. (2011). Fish farms, parasites, and predators: implications for salmon population dynamics. *Ecological Applications, 21*(3), 897-914.

Lackey, R. (2013). Saving wild salmon: a 165 year policy conundrum. *Dubach Workshop: Science and Scientists in the Contemporary Policy Process.* Portland: Oregon State University.

Lackey, R., Lach, D., & Duncan, S. (2006). *Salmon 2100: the future of wild Pacific salmon.* (R. Lackey, D. Lach, & S. Duncan, Eds.) Bethesda, Maryland, USA: American Fisheries Society.

Laetz, C., Baldwin, D., Collier, T., Hebert, V., Stark, J., & Scholz, N. (2009). The synergistic toxicity of pesticide mixtures: implications for risk assessment and conservation of endangered Pacific salmon. *Environmental Health Perspectives, 117*(3), 348-353. doi:10.1289/ehp.0800096

Lamborg, C., Hammerschmidt, C., Bowman, K., Swarr, G., Munson, K., Ohnemus, D., . . . Saito, M. (2014). A global inventory of anthropogenic mercury based on water column measurements. *Nature, 512*, 65-68. doi:10.1038/nature13563

Laurel, B., Copeman, L., Iseri, P., Spencer, M., Hutchinson, Nordtug, T., . . . Incardona, J. (2019). Embryonic crude oil exposure impairs growth and lipid allocation in a keystone Arctic forage fish. *iScience, 19*, 1101-1113. doi:10.1016/j.isci.2019.08.051

Lepofsky, D., Trost, T., & Morin, J. (2007). Coastal Salish Interaction: A view from the inlets. *Canadian Journal of Archaeology, 31*, 190-223.

Lichatowich, J. (1999). *Salmon without rivers: A history of the pacific salmon crisis.* Washington DC: Island Press.

Lluch-belda, D., Crawford, R., Kawasaki, T., MacCall, A., Parrish, R., Schwartzlose, R., & Smith, P. (1989). Worldwide fluctuations of sardin and anchovy stocks: the regime problem. *South African Journal of Marine Science, 8*, 195-205. Retrieved from https://swfsc-publications.fisheries.noaa.gov/publications/CR/1989/8937.PDF

Lundin, J., Chittaro, P., Ylitalo, G., Kern, J., Kuligowski, D., Sol, S., . . . Scholz, N. (2021). Decreased growth rate associated with tissue contaminants in juvenile chinook salmon out-migrating through an industrial waterway. *Environmental Science & Technology*. doi:10.1021/acs.est.1c01526

MacDonald, B., Grant, S., Wilson, N., Patterson, D., Robinson, K., Boldt, J., . . . Selbie, D. (2020). State of the Salmon: Informing the survival of Fraser Sockeye returning in 2020 through life cycle observations. *Canadian Technical Report of Fisheries and Aquatic Sciences 3398*, 76pp.

MacDonald, D., Sinclair, J., Crawford, M., Prencipe, H., & Meneghetti, M. (2011). *Potential effects of contaminants on Fraser River sockeye salmon - Technical report 2.* MacDonald Environmental Sciences Ltd. . Vancouver: The Cohen Commission of Inquiry into the decline of sockeye salmon in the Fraser River.

Macdonald, R., Ikonomou, M., & Paton, D. (1998). Historical inputs of PCDDs, PCDFs, and PCBs to a British Columbia Interior Lake: The effect of environmental controls on pulp mill emissions. *Environmental Science and Technology, 32*(3), 331-337.

Mackas, D., & Harrison, P. (1997). Nitrogenous nutrient sources and sinks in the Juan de Fuca Strait/Stait of Georgia/Puget Sound esturaine system: assessing the potential for eutrophicatin. *Estuarine, Coastal and Shelf Science, 44*, 1-21.

Marchak, P. (1983). *Green Gold: The forestry industry in British Columbia.* Vancouver: University of British Columbia Press.

Marty, G., Saksida, S., & Quinn, T. (2010). Relationship of farm salmon, sea lice, and wild salmon populations. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 22599-22604. doi:10.1073/pnas.1009573108

Mawani, R. (2009). *Colonial Proximities- crossracial encounters and juridical truths in British Columbia, 1871-1921.* Vancouver: UBC Press.

Maxey, J., Hartstein, N., Then, A., & Barrenger, M. (2020). Dissolved oxygen consumption in a fjord-like estuary, Macquarie Harbour, Tasmania. *Estaurine, Coastal and Shelf Science, 246*, 107016. doi:10.1016/j.ecss.2020.107016

McFarlane, G., & Beamish, R. (1998). Sardines return to British Columbia Waters. *Proceedings of 7th Annual PICES Meeting-Volume: PICES Science Report 10.* Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.360.1199&rep=rep1&type=pdf

Merriam, W. (1954). Conservation of the Fraser River sockeye salmon. *Yearbook of the Association of Pacific Coast Geographers, 16*, 46-54.

Miller, A., Elliott, J., Elliott, K., Guigueno, M., Wilson, L., Lee, S., & Idrissi, A. (2015). Brominated flame retardant trends in aquatic birds from the Salish Sea region of the west coast of North America, including a mini-review of recent trends in marine and estuarine birds. *Science of the Total Environment, 502*, 60-69. doi:10.1016/j.scitotenv.2014.09.006

Miller, A., Elliott, J., Elliott, K., Lee, S., & Cyr, F. (2015). Temporal trends of perfluoralkyl substances (PFAS) in eggs of coastal and offshore birds: increasing PFAS levels associated with offshore bird species breeding on the Pacific coast of Canada and wintering near Asia. *Environmental Toxicology and Chemistry, 34*, 1799-1808. doi:10.1002/etc.2992

Mordecai, G., Miller, K., Bass, A., Bateman, A., Teffer, A., Caleta, J., . . . Joy, J. (2021). Aquaculture mediates global transmission of a viral pathogen to wild salmon. *Science Advances, 7*, eabe2592. doi:10.1139/facets2021-0102

Morin, J., & Evan, A. (2022). *Historical ecology in Burrand Inlet: Summary of historic, oral history, ethnographic and traditional use information.* Vancouver: The University of British Columbia.

Morton, A., Routledge, R., Hrushowy, S., Kibenge, M., & Kibenge, F. (2017). The effect of exposure to farmed salmon on piscine orthoreovirus infection and fitness in wild Pacific salmon in British Columbia, Canada. *PLoS ONE, 12*(12), e0188793. doi:10.1371/journal.pone.0188793

Mulvihill, P., Morrison, W., & MacIntyre, S. (2005, Summer). Water, Gold and Obscurity: British Columbia's Bullion Pit. *The Northern Review*, pp. 197-210.

Nekouei, O., Vanderstichel, R., Ming, T., Kaukinen, K., Thakur, K., Tabata, A., . . . Miller, K. (2018). Detection and assessment of the distribution of infectious agents in juvenile Fraser River sockeye salmon, Canada, in 2012 and 2013. *Frontiers in MIcrobiology, 9*, 3221. doi:10.2289/fmicb.2018.03221

Nelitz, M., Porter, M., Parkinson, E., Wieckowski, K., Marmorek, D., Bryan, K., . . . Abraham, D. (2011). *Evaluating the status of Fraser River sockeye salmon and role of freshwater ecology in their decline.* Vancouver: ESSA Technologies. Cohen Commission Technical Report 3. Retrieved from https://www.researchgate.net/publication/274721543_Evaluating_the_status_of_Fraser_River_sockeye_salmon_and_role_of_freshwater_ecology_in_their_decline

Nener, J., & Wernick, B. (1997). *Fraser River Basin Strategic Water Quality Plan-Lower Fraser River: Fraser Delta, Pitt-Stave, Chilliwack and Harrison-Lillooet Habitat Management Areas.* Vancouver: Habitat and Enhancement Branch, Fisheries and Oceans Canada. Retrieved from https://www.researchgate.net/profile/Barbara-Wernick/publication/259482042_Fraser_River_Basin_Strategic_Water_Quality_Plan_Lower_Fraser_River_Fraser_Delta_Pitt-Stave_Chilliwack_and_Harrison-Lillooet_Habitat_Management_Areas/links/56e8366008ae9aecadbadded/

Newell, D. (1994). *Tangled Webs of History: Indians and the Law in Canada's Pacific Coast Fisheries.* Toronto: University of Toronto Press.

Noel, M., Dangerfield, N., Hourston, R., Belzer, W., & Shaw, P. (2009). Do trans-Pacific air masses deliver PBDEs to coastal British Columbia, Canada? *Environmental Pollution, 157*, 3404-3412. doi:10.1016/j.envpol.2009.06.025

Noel, M., Jeffries, S., Lambourn, D., Telmer, K., Macdonald, R., & Ross, P. (2016). Mercury accumulation in harbour seals from Northeastern Pacific Ocean: The role of transplacental transfer, lactation, age and location. *Archives of Environmental Contamination and Toxicology, 70*, 56-66. doi:10.1007/s00244-015-0193-0

Northcote, T., & Atagi, D. (1997). Pacific salmon abundance trends in the Fraser River watershed compared with other British Columbia systems.

O'Neal, S., & Woody, C. (2011). *Canada's Fraser River-Reasons for sockeye salmon declines with a comparison to Bristol Bay.* Fisheries Resaerch and Consulting www.fish4thefuture.com. Retrieved from http://www.pebblescience.org/pdfs/Fraser_River_White_Paper_22_Aug_2011.pdf

Ormsby, M. (1945). Agricultural Development in British Columbia. *Agricultural History, 19*(1), 11-20.

Orndorff, A. (2017). *Evaluating the effects of sedimentation from forest roads: a review.* University of Florida. Retrieved from https://soils.ifas.ufl.edu/media/soilsifasufledu/sws-main-site/pdf/technical-papers/Orndorff_Adam_Immediate_Release.pdf

Pauly, D. (1995). Anecdotes and the Shifting Baseline Syndrome of Fisheries. *Trends in Ecology and Evolution, 10*(10), 430. doi:10.1016/s0169-5347(00)89171-5

Peacock, S., Krkosek, M., Proboszcz, S., Orr, C., & Lewis, M. (2013). Cessation of a salmon decline with control of parasites. *Ecological Applications, 23*(3), 606-620.

Peter, K., Z, T., C, W., Lin, P., White, S., Du, B., . . . Kolodziej, E. (2018). Using high-resolution mass spectrometry to identify organic contaminants linked to urban stormwater mortality syndrome in coho salmon. *Environmental Science & Technology, 52*, 10317-10327. doi:10.1021/acs.est.8b03287

Petticrew, E., Albers, S., Baldwin, S., Carmack, E., Dery, S., Gantner, N., . . . Vagle, S. (2015). The impact of a catastrophic mine tailings impoundment spill into one of North America's largest fjord lakes: Quesnel Lake, British Columbia, Canada. *Geophysical Research Letters, 42*, 3347-3355. doi:10.1002/2015GL063345.

Polinski, M., Marty, G., Snyman, H., & Garver, K. (2019). Piscine orthoreovirus demonstrates high infectivity but low virulence in Atlantic salmon of Pacific Canada. *Scientific Reports, 9*, 3297. doi:10.1038/s41598-019-40025-7

Price, M., English, K., Rodenberger, A., MacDuffee, M., & Reynolds, J. (2017). Canada's Wild Salmon Policy: an asessment of conservation progress in British Columbia. *Canadian Journal of Fisheries and Aquatic Science, 74*, 1507-1518. doi:10.1139/cjfas-2017-0127

Purcell, M., Powers, R., Taksdal, T., McKenney, D., Conway, C., Elliot, D., . . . Winton, J. (2020). Consequences of Piscine orthoreovirus genotype 1 (PRV-1) infections in Chinook salmon (Oncorhynchus tshawytscha), coho salmon (O. kisutch) and rainbow trout (O. mykiss). *Journal of Fish Diseases, 43*, 719-728. doi:10.1111/jfd.13182

Rehberger, K., Werner, I., Hitzfeld, B., Segner, H., & Vaumann, L. (2017). 20 years of fish immunotixcology- what we know and where we are. *Critical reviews in Toxicology*, 1-18. doi:10.1080/10408444.2017.1288024

Reimchen, T., & Fox, C. (2013). Fine-scale spatiotemporal influences of salmon on growth and nitrogen signatures of Sitka spruce tree rings. *BMC Ecology, 13*(38). doi:10.1186/1472-6785-13-38

Rensel, J., Haigh, N., & Tynan, T. (2010). Fraser river sockeye salmon marine survival decline and harmful blooms of Heterosigma akashiwo. *Harmful Algae, 10*, 98-115. doi:10.10116/j.hal.2010.07.005

Richardson, J., & Healey, M. (1996). A healthy Fraser River? How will we know when we achieve this state? *Journal of Aquatic Ecosystem Health, 5*, 107-115. doi:10.1007/BF00662799

Ricker, W. (1954). Stock and recruitment. *Jornal of the Fisheries Research Board of Canada, 11*(5), 559-623. doi:10.1139/f54-039

Ricker, W. (1987). *Effects of the fishery and obstacles to migration on the abundance of Fraser River Sockeye Salmon (Oncorhynchus nerka).* Pacific Biological Station, Fisheries Research Branch. Nanaimo: Department of Fisheries and Oceans.

Roch, M., McCarter, J., Matheson, A., Clark, M., & Olafson, R. (1982). Hepatic metallothionein in rainbow trout (Salmo gairdneri) as an indicator of metal pollution in the Campbell River system. *Canadian Journal of Fisheries and Aquatic Sciences, 39*(12), 1596-1681.

Roch, M., Nordin, R., Austin, A., McKean, C., Deniseger, C., Kathman, R., . . . Clark, M. (1985). The effects of heavy metal contamination no the aquatic biota of Buttle Lake and the Campbell

River drainage (Canada). *Archives of Environmental Contamination and Toxicology, 14*, 347-362.

Rogers, I., Birtwell, I., & Kruzynski, G. (1990). The Pacific Eulachon)Thaleichthys pacificus) as a pollution indicator organism in the Fraser River estuary, Vancouver, British Columbia. *The Science of the Total Environment, 97/98*, 713-727.

Roon, D., Dunham, J., & Groom, J. (2021). Shade, light, and stream temperature responses to riparian thinning in second-growth redwood forests of northern California. *PLoS ONE, 16*(2), e0246822. doi:10.1371/journal.pone.0246822

Ross, G., & Ivarson, K. (1981). Th occurence of basic ferric sulfates in some Canadian soils. *Canadian Journal of Soil Science, 61*, 99-107. Retrieved from https://cdnsciencepub.com/doi/pdf/10.4141/cjss81-011

Ross, P., Chastain, S., Vassilenko, E., Etemadifar, A., Zimmermann, S., Quesnel, S.-A., . . . Williams, B. (2021). pervasive distribution of polyester fibres in the Arctic ocean is driven by Atlantic inputs. *Nature Communications, 12*(106). doi:10.1038/s41467-020-20347-1

Ross, P., Couillard, C., Ikonomou, M., Johannessen, S., Lebeuf, M., Macdonald, R., & Tomy, G. (2009). Large and growing environmental reservoirs of Deca-BDE present an emerging health risk for fish and marine mammals. *Marine Pollution Bulletin, 58*, 7-10. doi:10.1016/j.marpolbul.2008.09.002

Ross, P., Ellis, G., Ikonomou, M., Barrett-Lennard, L., & Addison, R. (2000). High PCB concentrations in free-ranging Pacific killer whales, Orcinus orca: effects of age, sex and dietary preferance. *Marine Pollution Bulletin, 40*, 504-515.

Ross, P., Kennedy, C., Shelley, L., Tierney, K., patterson, D., Fairchild, W., & Macdonald, R. (2013). The trouble with salmon: relating pollutant exposure to toxic effect in species with transformational life histories and lengthy migrations. *Canadian Journal of Fisheries and Aquatic Science, 70*, 1252-1264. doi:10.1139/cjfas-2012-0540

Ross, P., Noel, M., Lambourn, D., Dangerfield, N., Calambokidis, J., & Jeffries, S. (2013). Declining concentrations of PCBs, PBDEs, PCDEs and PCNs in harbor seals from the Salish Sea. *Progress in Oceanography, 115*, 160-170.

Ross, P., Walters, K., Yunker, M., & Lo, B. (2022). *A lake re-emerges: Analysis of contaminants in the Sema:th Xo:tsa (Sumas Lake) region following the BC floods of 2021.* Sidney: Raincoast Conservation Foundation.

Saskida, S. (2015). *A summary of sea lice in BC- wild and farmed monitoring and management.* Sea to Sky Veterinary Services. Retrieved from https://myasc.asc-aqua.org/netapp/FileHandler.ashx?id=1CE63EA5-77DB-4977-93B6-A2B5CD345D92

Schweigert, J., Boldt, J., Flostran, L., & Cleary, J. (2010). A review of factors limiting recovery of Pacific herring stocks in Canada. *ICES Journal of Marine Science, 67*, 1903-1913.

Scott, J. (1998). *Seeing Like a State: How certain schemes to improve the human condition have failed.* New Haven: Yale University Press.

Semeniuk, R. (2003). How bears feed salmon to the forest. *Natural History*, pp. 3-4.

Shaffer, A. (2021). Piscine Orthoreovirus (PRV) and ecoparasites of young of the year juvenile herring, Clupea pallasii, of the Salish Sea. *Osprey: The International Journal of Salmon and Steelhead Conservation, 98*, 17-21.

Shang, D., Macdonald, R., & Ikonomou, M. (1999). persistence of nonylphenol ethoxylate surfactants and their primary degradation products in sediments from near a municipal outfall in the Strait of Georgia, British Columbia, Canada. *Environmental Science & Technology, 33*(9), 1366-1372. doi:10.1021/es980966z

Shoeib, M., Harner, T., Webster, G., & Lee, S. (2011). Indoor sources of poly- and perfluorinated compounds (PFCS) in Vancouver, Canada: implications for human exposure. *Environmental Science & Technology, 45*(19), 7999-8005. doi:10.1021/es103562v

Slaney, T., Hyatt, K., Northcote, T., & Fielden, R. (1996). Status of anadromous salmon and trout in British Columbia and Yukon. *Fisheries, 21*(10), 20-35.

Smith, D. (1987). *Mining America: The industry and the environment 1800-1980.* Lawrence: University Press of Kansas.

Smith, D. (2001). Salmon Populations and the Sto:lo Fishery. In K. Carlson, *A Sto:lo Coast Salish Historical Atlas* (p. 120). Vancouver: Douglas & McIntyre.

Smith, O. (1940). Placer mining silt and its relation to salmon and trout on the Pacific coast. *Transactions of the American Fisheries Society, 69*(1), 225-230. doi:10.1577/1548-8659(1939)69[225:PMSAIR]2.0.CO;2

Stephen, C., Stitt, T., Dawson-Coates, J., & McCarthy, A. (2011). *Assessment of the potential effects of diseases present in salmonid enhancement facilities on Fraser River sockeye salmon.* Vancouver: Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River.

Swanton, J. (1905). *Contributions to the Ethnologies of the Haida (2nd edition).* New York: EJ Brill, Leiden and GE Stechert.

Szenasy, E. (1998). *Toxicity testing for guideline development of selected pulp mill chemicals that are priority substances in the Fraser River DOE FRAP 1998-12.* Vancouver: Environment Canada.

Taylor, J. (1999). *Making salmon: an environmental history of the northwest fisheries crisis.* Seattle: University of Washington Press.

Teclaff, L. (1985). *Water Law in Historical Perspective.* Buffalo, N.Y.: William S Hein Co.

The Fraser Basin Council. (2013). Bridge between nations- A history of first nations in the Fraser River basin. Vancouver, British Columbia, Canada. Retrieved from https://www.fraserbasin.bc.ca/_Library/Ab_NonAb_Relations/bridge_between_nations.pdf

(1997). *The Management of Agricultural Wastes in the Lower Fraser Valley Report 9- Summary Report- A working document.* Environment Canada, Fisheries and Oceans, Ministry of Environment, Lands and Parks, Ministry of Agriculture Fisheries and Food. Retrieved from https://a100.gov.bc.ca/pub/eirs/finishDownloadDocument.do?subdocumentId=1862

Therriault, T., McDiarmid, A., Wulff, W., & Hay, D. (2002). *Review of Surf Smelt (Hypomesus pretiosus) biology and fisheries, with suggested managment options for British Columbia.* Pacific Biological Station. Nanaimo: Fisheries and Oceans Canada.

Thompson, J., Macdonald, R., & Wong, C. (1980). Mercury geochemistry in sediments of a contaminated fjord of Coastal British Columbia. *Geochemical Journal, 14*, 71-82.

Tian, Z., Gonzalez, M., Rideout, C., Zhao, H., Hu, X., Wetzel, J., . . . Kolodziej, E. (2022). 6PPD-quinone: revised toxicity assessment and quantification with a commercial standard. *Environmental Science & Technology Letters, 9*, 140-146. doi:10.1021/acs.estlett.1c00910

Tian, Z., Zhao, H., Peter, K., Gonzalez, M., Wetzel, J., Wu, C., . . . Dodd, M. (2020). A ubiquitous tire rubber-derived chemical induces acute mortality in coho salmon. *Science*. doi:10.1126/science.abd6951

Tierney, K., Sampson, J., Ross, P., Sekela, M., & Kennedy, C. (2008). Salmon olfaction is impaired by an environmentally realistic pesticide mixture. *Environmental Science & Technology, 42*, 4996-5001. doi:10.1021/es800240u

Tierney, K., Taylor, A., Ross, P., & Kennedy, C. (2006). The alarm reaction of coho salmon parr is impaired by the carbamate fungicide IPBC. *Aquatic Toxiciology, 79*, 149-157. doi:10.1016/j.aquatox.2006.06.003

Torrissen, O., Jones, S., Asche, F., Guttormsen, A., Skilbrei, O., Nilsen, F., . . . Jackson, D. (2013). Salmon lice-impact on wild salmonids and salmon aquaculture. *Journal of Fish Diseases, 36*, 171-194. doi:10.1111/jfd.12061

Tracy, A., Pielmeier, M., Yoshioka, R., Heron, S., & Harvell, C. (2019). Increases and decreases in marine disease reports in an era of global change. *Proceedings of the Royal Society of Biological Sciences, 286*, 20191718. doi:10.1098/RSPB.2019.1718

Urbina, M., Cumillaf, J., Paschke, K., & Gebauer, P. (2019). Effects of pharmaceuticals used to treat salmon lice on non-target species: Evidence from a systemic review. *Science of the Total Environment, 649*, 1124-1136. doi:10.1016/j.scitotenv.2018.08.334.

Valdes-Castro, V., & Fernandez, C. (2021). Effect of three pesticides used in salmon farming on ammonium uptake in central-southern and northern Patagonia, Chile. *frontiers in Marine Science, 7*, 602002. doi:10.3389/fmars.2020.602002

van de Vosse, H. (2008). *Mountain Pine Beetle Infestation: Hydrological Impacts.* EDI Environmental Dynamics Inc. Prince George: Ministry of Environment-Mountain Pine Beetle Action Team. Retrieved from https://a100.gov.bc.ca/pub/eirs/finishDownloadDocument.do;jsessionid=427F8F2977181EEA3A56485BD8183F75?subdocumentId=4971

Vassilenko, E., Watkins, M., Mertens, J., Posacka, A., Patankar, S., & Ross, P. (2021). Domestic laundray and microfibre pollution: a comprehensive assessment of fiber shedding from consumer apparel textiles. *PLOS ONE*. doi:10.1371/journal.pone.0250346

Wainwright, P., Humphrey, B., Drinnan, W., & Fox, M. (1995). *Review of information on the environmental occurrence of chemical contaminants and conditions of environmental degradation in the aquatic environment of th Fraser Basin.* Environment and Conservation Branch. North Vancouver: Environment Canada.

Waldichuk, M. (1962). Some water pollution problems connected with disposal of pulp mill wastes. *The Canadian Fish Culturalist, 31*, 3-34. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/171231_1962.pdf

Ward, A., Thistle, M., Ghandi, K., & Currie, S. (2013). Copper interacts with nonylphenol to cancel the effect of nonylphenol on fish chemosensory behaviour. *Aquatic Toxicology, 142-143*, 203-209. doi:10.1016/j.aquatox.2013.08.010

Ware, D. (1991). Climate, predators and prey: behavour of a linked oscillating system. In T. Kawasaki, S. Tanaka, Y. Toba, & A. Taniguchi (Eds.), *Long-term variability of pelagic fish populations and their environment* (pp. 279-291). Tokyo: Pergamon Press.

Ware, D. (1999). *Life history of Pacific sardine and a suggested framework for determining a B.C. catch quota.* Ottawa: Fisheries and Oceans Canada.

Weinstein, M. (2000). Pieces of the pPuzzle: Solutions for Community-Based Fisheries management from Native Canadians, Japanese Cooperatives, and Common Property Researchers. *The Georgetown International Environmental Law Review, 12*, 375-412.

West, J., O'Neill, S., & Ylitalo, G. (2008). Spatial extent, magnitude, and patters of persistent organochlorine pollutants in Pacific herring (Clupea pallasi) popultions in the Puget Sound (USA) and Strait of Georgia (Canada). *Science of the Total Environment, 394*, 369-378. doi:10.1016/j.sciotenv.2007.12.027

Wilson, J. (1987, Winter). Forest Conservation in British Columbia, 1935-1985: reflections on a barren debate. *BC Studies, 76*, p. 22.

Wilson, J., Addison, R., Martens, D., Gordon, R., & Glickman, B. (2000). Cytochrome P450 1A and related measurements in juvenile chinook salmon (Oncorhynchus tshawytscha) from the Fraser River. *Canadian Journal of Fisheries and Aquatic Science, 57*, 405-413. doi:10.1139/f99-251

Wood, A., Johnston, B., Farrell, A., & Kennedy, C. (1996). Effects of didecyldimethylammonium chloride (DDAC) on the swimming performance, gill morphology, disease resistance, and biochemistry of rainbow trout (Oncorhynchus mykiss). *Canadian Journal of Fisheries Aquatic Science, 53*(11), 2424-2432. doi:10.1139/f96-201

Wood, P. (2021). *Intact forests, safe communities.* Sierra Club BC. Retrieved from https://sierraclub.bc.ca/wp-content/uploads/2021-Forest-Climate-Risk-Assessment-Report-final-February.pdf

Yoshiyama, R., Fisher, F., & Moyle, P. (1998). Historical abundance and decline of chinook salmon in the central valley region of California. *North American Journal of Fisheries Management, 18*, 487-521.

Yunker, M., Macdonald, R., Vingarzan, R., Mitchell, R., Goyette, D., & Sylvestre, S. (2002). PAHs in the Fraser River basin: a critical appraisal of PAH ratios as indicators of PAH source and composition. *Organic Gechemistry, 33*, 489-515.

Zhang, Y., Polinski, M., Morrison, P., Brauner, C., Farrell, A., & Garver, K. (2019). High-load reovirus infections do not imply physiological impairment in salmon. *Frontiers in Physiology, 10*(114). doi:10.3389/fphys.2019.00114

Zwolinski, J., & Demer, D. (2012). A cold ocaenographic regime with high exploitation rates in the Northeast Pacific forecasts a collapse of the sardine stock. *PNAS, 109*(11), 4175-4180. doi:10.1073/pnas.1113806109

Appendix 1 – Legislation governing Fraser River salmon

The table below has been drawn from (Cohen, 2012) and the website of the Department of Fisheries and Oceans, Canada (DFO)- https://www.dfo-mpo.gc.ca/acts-lois/index-eng.htm. It is a detailed but not exhaustive list of legislation and regulation which applies to management of the Fraser River salmon fishery.

International law	
United Nations Convention on the Law of the Sea	Canada ratified in 2003. Governs fisheries and protection of the marine environment. Has obligation to prevent, reduce and control marine pollution from all sources. Canada has the primary interest in and responsibility for the Fraser River salmon.
Convention for the Protection, Preservation and Extension of the Sockeye Salmon Fisheries of the Fraser River System (1937 Convention)	Established the International Pacific Salmon Fisheries Commission.
Agreement between the Government of Canada and the Government of the U.S.A. concerning Pacific Salmon (Pacific Salmon Treaty)	Ratified in 1985 replaced the 1937 convention. Provides bilateral management of salmon acknowledging management may affect the other countries stocks or catches. Each party agreed to prevent overfishing and provide optimum production and receive benefits equivalent to the production of salmon originating in its waters. The commissioners on the Pacific Salmon Commission may adjust fishing times and areas. Require DFO to issue annual report on catch and estimate the run size and spawning escapement required, estimate total allowable catch in the upcoming season.
Convention on the Conservation of Anadromous Stocks of the North Pacific Ocean	Ratified 1993. Sets out an enforcement scheme within the Convention Area to minimise incidental catch of anadromous fish.
Convention for a North Pacific Marine Science Organization	Ratified in 1991 establishes the North pacific marine Science Organisation to promote and coordinate scientific research and information sharing related to the North Pacific Ocean.
Convention on Biological Diversity	Ratified in 1992. Seeks to conserve biological diversity requiring Canada to monitor components of biological diversity important for conservation and sustainable use and identify processes that may have adverse impacts.

	Promotes conservation of ecosystems and natural habitats to maintain their salmon populations. Requires signatories to rehabilitate and restore degraded ecosystems and promote recovery of threatened species.
Code of Conduct for Responsible Fisheries (FAO Code of Conduct)	Voluntary code provides principles for conservation and development of fisheries. Signatories are to take into account the precautionary principle
Minimata Convention	Canada ratified convention which came into force in 2017
Key federal legislation managing fisheries and pollution	
Department of Fisheries and Oceans Act	Sets out powers, duties, and functions of minister. Empowers minister to enter agreements with any province (provincial agency) regarding fisheries programs.
Fisheries Act	Primary statutory authority for management and regulation of fisheries in Canada. Provides minister powers to issue licences and leases for fisheries or fishing Provides basis for environmental protection of fish and fish habitat from destruction by "means other than fishing"[80] and by the general and specific prohibitions on depositing pollutants in Canadian fisheries waters[81]. *Aquaculture Activities Regulations* cover licencing, environmental management, biofouling, reporting of pests and disease and deposition of a deleterious substance (eg fish medicine).
Oceans Act	Mandates an integrated ecosystem -based approach to management of ocean activities, including establishment of marine protected areas based on the three principles of: sustainable development; integrated management; and the precautionary principle. Provides that the Canadian Coast Guard is the lead agency for ship origin and mystery source pollution incidence in Canadian waters.
Coastal Fisheries Protection Act	Licences fishing activities, landing and sale of fish.
Species at Risk Act	Prescribes the minister for fisheries and oceans to be responsible listed aquatic species to consider their habitats,

[80] *Fisheries Act,* RSC 1985, c. F- 14, s. 32
[81] *Fisheries Act,* RSC 1985, c. F-14, s. 36

	environmental assessments and provide advice on recovery and action plans to prevent a species from being extirpated or made extinct. DFO shared responsibility with Environment Canada and Parks Canada.
Canadian Environmental Assessment Act	Requires environmental assessment of projects which require authorization under the *Fisheries Act* which may destroy fish by means other than fishing, harmfully alter, disrupt, or destroy fish habitat or results in the deposition of deleterious substances in water frequented by fish.
Canadian Environmental Protection Act	Commits to precautionary principle to protect the environment and human health by managing marine pollution, disposal at sea, toxic substances, and other sources of pollution. Issues environmental objectives, guidelines, and codes of practice to prevent and reduce marine pollution from land-based sources. Enables issuing of permits to authorize disposal of waste. Maintains the National Pollutant Release Inventory. Directs monitoring of environmental quality and research in relation to pollution and contamination. Lists toxic substances and requires pollution prevention plans for them, where used or released. Provides powers to control nutrients and land-based pollution both point and diffuse source, where they may directly or indirectly result in hazards to human health, harm to living resources or marine ecosystems, damage to amenities or interference with other legitimate uses of the sea[82].
Canada Water Act	Provides for co-operative management of water quality and resource planning and allows for federal action if an agreement of action cannot be reached with a provincial government.
Health of Animals Act	Defines list of reportable diseases.
Pest Control Products Act	Regulates pest control products through risk assessments.
Food and Drugs Act	Regulates substances sold for use in diagnosis treatment and mitigation of disease including disinfectants.

[82] *Canadian Environmental Protection Act,* SC 1999, c. 33, s. 120.

National Marine Conservation Areas Act	Establishes marine conservation areas to protect and conserve representative marine areas for the benefit, education, and enjoyment of the people of Canada and the world.
Canada Marine Act 1998	Implement policies that provide Canada with marine infrastructure such as ports, to support national social and economic objectives. Provide high level of safety and environmental protection
Canada Shipping Act 2001	Regulates marine transport and commerce to promote safety and protect environment from damage due to navigation and shipping activities.
Regulations under the *Fisheries Act*	
Fishery (General) Regulations, SOR/93-53	Establish, vary fishery closures, fishing quotas, fish size and weight limits Create licences and registration Identify fishing vessels and gear Define role of fishery observers Define enforcement of *Fisheries Act*
Pacific Fishery Regulations, 1993, SOR/93-54	Part VI govern the salmon fishery
Pacific Fishery Management Area Regulations, 2007, SOR/2007-77	Define the geographic boundaries of management areas and sub-areas which are used to describe when certain fisheries are opened and closed
British Columbia Sport Fishing Regulations, 1996, SOR/96-137	Define opening and closing times, fishing quotas and size limits for sports fisheries in British Columbia
Aboriginal Communal Fishing Licences Regulations, SOR/93-332	Issue licences which regulate communal fishing activities
Management of Contaminated Fisheries Regulations, SOR/90-351	Authorizes DFO regional direction to close a fishery where fish are contaminated and pose a danger to human health.
Chlor-Alkali mercury Liquid Effluent Regulations, CRC, c.811	During the operation of mercury-cell Chlor Alkali plants this regulation made an exemption to permit mercury discharges via effluent and air, which were otherwise prohibited under the *Fisheries Act*. When the last plants in were closed in 2008 this provision was repealed in 2018.
Water Sustainability Act	Defines the purposes for which water may be diverted from a stream or aquifer including conservation, domestic, industrial, agricultural irrigation, mineralized water for drinking or bathing, land improvement, mining, oil and gas, power, storage and waterworks.
Forest and Range Practices Act	Governs forest and range activities on public lands in B.C. during forest planning, road

	building, timber harvesting, reforestation and livestock grazing
Oil and Gas Activities Act	Regulate oil and gas activities in B.C. that provide for sound development of oil and gas sector, by fostering a healthy environment, a sound economy and social well-being.
Mines Act	Provides regulatory framework for mining exploration, development, construction, production, closure, reclamation, and abandonment.
Land Act	Allows granting of land and issue of Crown land tenure in form of leases, licences, permits and rights-of-way.
Environmental Assessment Act	Provides a mechanism to review major projects to assess potential impacts to ensure they meet environmental, economic, and social sustainability goals.
Environmental Management Act	Controls of waste/emission releases including hazardous waste, biomedical waste, litter, sewage from business and industry through permits, codes of practice and regulation.
Riparian Areas Protection Act	Requires local government to protect riparian areas during residential, commercial, and industrial development by ensuring a Qualified Environmental Professional (QEP) conducts a science-based assessment of proposed activities.
Agricultural Land Commission Act	Preserve and encourage farming of land within agricultural land reserves.
Pacific Aquaculture Regulations, SOR/2010-270	Aquaculture is managed as a fishery by DFO who issue licences for the activity.
Pulp and Paper Effluent Regulations, SOR/92-269	Defines and authorizes the limitations of deposition of certain deleterious substances that can be present in pulp and paper mill effluent. Effluent that is acutely toxic to fish cannot be released and limits are set on suspended solids and biochemical oxygen demand.
Provincial statutes which regulate aspects of the Fraser River salmon fishery	
BC *Fisheries Act,* RSBC 1996, c.149	Licences commercial fisheries, fish processing plants, buying stations and recreational fishers. Makes regulations for safe and orderly aquaculture
BC *Water Act*, RSBC 1996, c. 483	Manages works in or about a body of water. *Water Regulation defines works* permitted under the *Water Act* such as restoration and maintenance of fish habitat.

BC *Wildlife Act*, RSBC 1996, c. 488	Manages interaction of people with wildlife including fish, requiring licences to fish non-tidal waters.
BC *Forest and Range Practices Act,* SBC 2002, c. 69	Regulates forestry activities that impact salmon habitat.
BC *Environmental Management Act*, SBC 2003, C.53	Provides authority to manage, protect and enhance the environment. Under the *Waste Discharge Regulation* prescribes which entities need to be authorized to discharge waste.
BC *Fish Protection Act*, SBC 1997, c.21	Prohibits bank to bank dams on designated rivers. Considers impacts of any water licencing on fish and fish habitat. Empowers council to protect and enhance riparian areas under the *Riparian Areas Regulation.*
BC *Fish Inspection Act*, RSBC 1996, c. 148	Regulates handling, processing, storing grading, packaging, marking, transporting, marketing and inspection of fish and fish products.
BC *Environmental Assessment Act,* SBC 2002, c.43	Applies to some mining, energy, water management, waste disposal, food processing, transportation, and tourist resort development projects.

Author's Acknowledgments

Dr. Landos wishes to acknowledge the following people who contributed to and/or supported preparation of these papers and made this work possible.

- To my partner, whose love and tolerance of me are boundless and amazing.
- To my son, who inspires me to make his future better.
- Mariann Lloyd Smith and Joanna Immig of the National Toxics Network, for their wise counsel, inspirational support, and refined editing.

- Bob McDonald, naturalist, for being a challenging, formidable thinker and valued mate.
- Peter Ross, Raincoast Conservation Foundation
- Don MacDonald