Fraser River Sockeye

1 Introduction

1.1 Motivation

Fisheries for Fraser River sockeye salmon were severely curtailed or eliminated for an unprecedented period of three years from 2007 to 2009. The low returns in 2009 attracted special attention because the pre-season forecast used by managers implied a harvestable surplus that never materialized. In Chilko Lake (see Figure 3), for example, smolt-to-adult survival of the smolts that went to sea in 2007 and will return from 2008 to 2011 may turn out to be, when all of the returns are counted, the lowest in the history of records that extend back to the 1950s. Most Fraser River sockeye salmon spend more than half of their lives in the sea (Gilbert, 1914) so any consideration of the cause of low abundance must take into account that the factors which are responsible for the decline may be found in salt water. A preliminary review of evidence implicated a marine cause for the poor returns[1].

A related issue arose from an observation that the productivity of Fraser River sockeye salmon, measured as a ratio of aggregate adult returns to total spawners in all populations (Fig. 1), has declined since the mid-1980s and may have reached its lowest level since the late 1940s in the 2007 ocean entry year. However, ascertaining whether or not this observation was solely marine in origin can be a challenge because returns per spawner are determined by factors affecting survival in both fresh and salt water. This issue can be examined using data from Chilko Lake where spawner-to-smolt, smolt-to-adult, and total survival (returns per spawner) have been estimated for many years.

While this report was being written in the summer of 2010, the largest return of Fraser River sockeye salmon since 1913 reached the British Columbia coast. Comments were requested by the Cohen Commission (hereinafter, the Commission) on the contrast with 2009 and previous years but an extensive analysis was not possible in the time allowed.

Fig. 1 Ratio of aggregate (all stocks) sockeye salmon returns to the Fraser River to aggregate female spawners. Source: Pacific Salmon Commission.

[1] http://www.sfu.ca/cs/science/resources/adaptingtochange/FraserSockeyeThinkTankStatement.pdf

1.2 Authorship – North Pacific Marine Science Organization

The North Pacific Marine Science Organization (PICES) is an international, intergovernmental marine science organization that was established by international convention in 1992 (Appendix 1). The current membership of the Organization includes Canada, Japan, People's Republic of China, Republic of Korea, Russian Federation, and the United States of America. They constitute all of the salmon-producing nations of the North Pacific except for North Korea.

The scientific committees of the Organization provide oversight of ocean/climate, fisheries science, biological oceanography, and marine environmental quality. The chairs of these committees and their relevant expert groups form the Science Board that is responsible for the science conducted by the Organization. The PICES Science Board is responsible for the scientific products of the Organization, including general oversight of the development of this report.

1.3 Organization of the Report

A primary objective of this report was to provide the Commission with a review of what is known about the ecology of Fraser River sockeye salmon in the sea. An historical approach was used so that an appreciation of what was learned, and when it was learned, can be ascertained. The basic material was organized around three life-history stages that correspond roughly to the age of sockeye salmon at sea. Each stage is considered separately in Sections 2 to 4. Section 2 reviews the coastal migration of Fraser River sockeye salmon postsmolts[2] and underyearlings through the Strait of Georgia and along the continental shelf. *Smolts* are juvenile sockeye salmon which have undergone the physiological changes to live in the ocean and have left the nursery lake where they have spent one or more years feeding and growing. This is to distinguish them from *underyearlings* which hatch and do not spend a winter in freshwater before entering the sea (Gilbert, 1914), however they may delay in sloughs and lagoons in the Fraser River delta (Birtwell *et al.*, 1987). The *postsmolt* stage is defined, arbitrarily, to begin with entry into salt water and end with the calendar year when ocean entry occurred. The coastal migration of postsmolts begins in April and continues throughout the summer and fall as the cohort migrates seaward from the Fraser River.

Section 3 is concerned with the offshore feeding migration beyond the continental shelf of *immature* sockeye salmon. This stage is defined, again arbitrarily, to cover the period from January 1 of the calendar year after the postsmolt year to the December 31 of the year before they return to spawn. The final phase, in Section 4, deals with sexual maturation and homeward migration to a natal stream. These individuals will be designated in this report as *maturing* sockeye salmon, again arbitrarily defined from January 1 in the year when maturation occurs. The durations of each of the final two phases varies somewhat among individuals but, overall, a total ocean phase of about 25 months is the most common among sockeye salmon in the Fraser River. Jacks (and jills) which mature after the postsmolt year do not have an immature phase according to this definition.

While it was not possible to describe in detail every study that has been conducted, it was possible to touch on those expeditions that have resulted in significant improvements in the understanding of Fraser River sockeye salmon. This perspective will provide a good background with which to compare any contemporary observations and provide the context for interpreting the questions of primary concern to the Commission. For the most part, the scientific history of Fraser River sockeye salmon can be determined by reviewing the results of publications that arose from each research project. However, some research programs produced data on Fraser River sockeye salmon for years but failed to produce data reports and/or failed to publish interpretations of the data. On those occasions when only the data were published, our approach was to analyze the data and report the results of those analyses. Likewise, if alternative interpretations of published results were possible, they were explored.

[2] The definitions of terms used in this report can be found in Appendix 2.

Because of the general lack of stage-specific estimates of mortality for the life-history stages described above, the overview of marine survival of all life-history stages was placed in Section 5. The physical, chemical, biological oceanography and climate that were relevant to the periods of interest to the Commission were grouped in Section 6. Finally, Section 7 contains the discussion of the major questions posed to the researchers by the Commission.

This report deals with what is known about Fraser River sockeye salmon at sea, *i.e.*, not all sockeye salmon. Where comparisons with other stocks help to provide a better perspective on the former, they have been made. In large part, this was necessary because the science of determining the origin of sockeye salmon caught at sea, with reasonable accuracy, has only recently been developed. The report excludes a consideration of the effects of toxins, parasitism, disease, and predation, as these topics were considered in other reports to the Commission.

Readers must keep in mind that there is no observation system for Fraser River sockeye salmon on the high seas (beyond the continental shelf). Research and monitoring in the Strait of Georgia since 1997 has focused on coho salmon and chinook salmon in July and September after many sockeye salmon postsmolts have left the area, and the Fisheries and Oceans Canada (DFO) high seas salmon program has focused on postsmolt surveys on the continental shelf since the late 1990s and is contributing to new understanding of this region (Grimes *et al.*, 2007). Therefore, during the period of years of interest to the Commission, there are virtually no observations of Fraser River sockeye salmon during about 75% of their life at sea, and the value of coincidental samples taken during their emigration from the Strait of Georgia is debatable.

This discussion of the Commission's two key questions is restricted in scope to an examination of the interconnections between climate, the ocean, and the fish at each oceanic life-history stage, *i.e.*, to what extent are "bottom-up" effects responsible for the status and trends of Fraser River sockeye salmon abundance. In simple terms, bottom-up forces are a result of the interplay of the physics, chemistry, and biology that provide for the growth and survival of sockeye salmon and other species at sea. For species that are resident on the west coast of British Columbia (not migratory), bottom-up forcing from year-to-year variations in phytoplankton at the base of the food web, through zooplankton production to fish production, has been reported (Ware and Thomson, 2005).

1.4 Research Directed at Salmon in the Ocean

> *The scientists I have known upon the river, men as great as they are obscure, came almost to worship the salmon and hid their worship under scientific jargon. Watching the inscrutable quest of the salmon, recognizing a principle beyond their power to explain, these men (though they would be the first to deny it) turn into religionists of a queer, incommunicable congregation. The greatest of them, a man who had spent his life and genius on the study of these fishes, once said to me, as we watched them surge up the river: "We really don't know anything about them. I don't think we ever will."*
>
> Bruce Hutchison, The Fraser, 1950[3]

Indeed, what the greatest of them (whoever s/he may have been) could not have anticipated was that one of the great unknowns, the whereabouts of Fraser River sockeye salmon at sea, would remain a mystery only until the mid-1950s when the newly formed scientific committees of the International North Pacific Fisheries Commission (INPFC) began their work. This tripartite Commission of Canada, Japan, and the United States was established in 1953 as a result of a clause in the San Francisco Peace Treaty that required it. In the 1930s, Japanese fishing fleets had been moving into the eastern Bering Sea to fish for salmon and the American and

[3] Bruce Hutchison (1901–1992) was Editor of the *Victoria Times* from 1950–1963 and the Editorial Director of the *Vancouver Sun* from 1963–1980; both are major newspapers in these cities.

Canadian governments did not want fish stocks that they had been conserving to be exposed to unregulated fishing by Japanese fishermen. When the INPFC was established, financial resources were made available by the Government of Canada to its Fisheries Research Board to resolve the many uncertainties about the life of salmon at sea. Much of what is known today about salmon at sea was a consequence of the Board's contribution to the international research program. Ocean-going studies of salmon at sea by Canadians were significantly reduced after the late 1960s.

High seas studies directed at salmon resumed in 1986 to investigate their potential exposure to the large-scale squid driftnet fishery (Bernard 1986; LeBrasseur *et al.*, 1987, 1988). The northern range of the target species, flying squid (*Ommastrephes bartrami*), was thought to overlap the southern end of the range of Pacific salmon. As a result, these surveys were directed at the southern fringe of the salmon distribution. The United Nations General Assembly declared a moratorium on large-scale driftnet fishing in the early 1990s; Canadian research cruises related to this study ended in 1990.

Surveys to test a thermal limit hypothesis to describe the oceanic range of salmon in the Gulf of Alaska began in 1995 (Welch *et al.*, 2002). After a few years of not catching salmon in the Gulf of Alaska beyond the continental shelf, it transformed into a successful coastal research program that, for the most part, focused on postsmolts and underyearlings in waters <200 m. As similar studies of juvenile salmon were being conducted in the United States, the coast-wide perspective, from California to Alaska, on postsmolt biology resulted in significant improvements in knowledge of this life history stage for all salmon species (Grimes *et al.*, 2007; Tucker *et al.*, 2009; Trudel *et al.*, 2009).

The first and most comprehensive review of the biology of sockeye salmon at sea was undertaken by the INPFC based on the results of its high seas research programme (Hanamura, 1966; Ricker 1966; French *et al.*, 1976). The first monograph on the sockeye salmon (in English) was published by the Fisheries Research Board of Canada (Foerster, 1968) and reviews and compilations appeared intermittently thereafter (Smith *et al.*, 1987; Burgner, 1991; Quinn, 2005). Reviews directed at Fraser River sockeye salmon first appeared in the early 20th century as scientific interest developed around variations in the fishery and recovery from the Hell's Gate rock slide in the river (Fig. 3; Babcock, 1918). The most comprehensive overview of Fraser River sockeye salmon was undertaken by Roos (1991) following the termination of the International Pacific Salmon Fisheries Commission, but it had a greater focus on the freshwater phases of sockeye salmon biology.

1.5 General Biology

There are seven species of Pacific salmon in British Columbia waters, namely sockeye salmon, pink salmon, chum salmon, coho salmon, chinook salmon, steelhead trout, and cutthroat trout, and all have anadromous ecotypes. They reproduce and incubate eggs in freshwater, move to salt water for a number of years to feed and grow, and then return to freshwater for spawning. Use of both the freshwater and oceanic environments implies important biological adaptations to each.

Fraser River sockeye salmon exhibit a diverse assemblage of life histories (Gilbert, 1914). Individuals can vary from a few months to a few years in age before migrating to sea. Once there, they can spend one to several years at sea before maturing and migrating back to their natal stream. On average, the duration of the oceanic phase is shorter for males than for mature females because of the former's tendency for some faster growing individuals to mature at an earlier age. As a consequence of this variability, the members of a single cohort can be exposed to very different freshwater and oceanic environments, depending on the year when they make the transition between these environments. This variability creates a bookkeeping challenge when comparing growth or survival or other aspects of biology to environmental variation. In general, the life history of sockeye salmon is relatively plastic so the durations of these phases are not fixed within a population. In the Fraser River, the dominant ecotype matures following the second winter at sea (see Appendix 3 for ecotypes by population).

1.5.1 Life cycle of sockeye salmon

The life cycle of Pacific salmon consists of a number of discrete life history phases, including spawning, incubation, rearing, migration to sea of the juveniles, feeding and growth in the ocean, return migration to the home stream, upstream migration of mature adults, and spawning. After spawning all Pacific salmon die.

In North America, sockeye salmon are economically the most important Pacific salmon, with the most complicated life cycle. They lay their eggs in nests dug in gravel beds in freshwater streams and rivers. The juveniles then migrate to the ocean, feed actively, and grow rapidly. Upon reaching maturity, after one, two, or more years in the ocean, depending on the population, they return to their freshwater home streams to spawn.

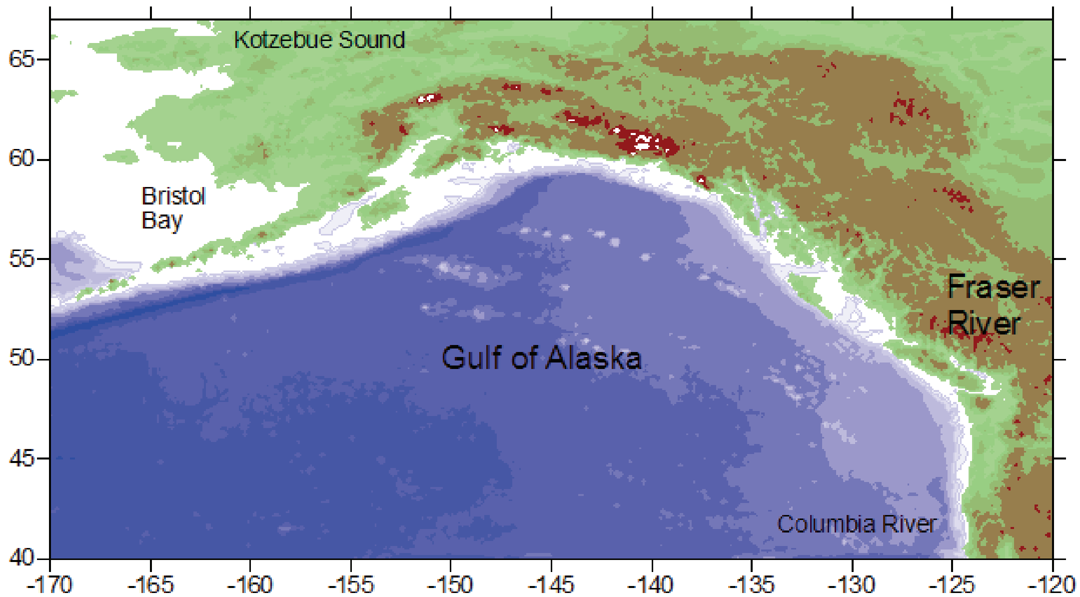

Fig. 2 Range of sockeye salmon in North America from the Columbia River to Kotzebue Sound, with colour shading representing bathymetry/topography. The continental shelf appears in white.

The geographic distribution of sockeye salmon covers vast areas of the North Pacific Ocean and adjacent landmasses during their life cycle. The North American spawning distribution ranges from the Columbia River northward to Kotzebue Sound in Alaska (Fig. 2), although during the last decade, they have been reported in the Arctic Ocean (Babaluk *et al.*, 2000). On the Asian side, sockeye populations are found from Cape Chaplina in the north, southward along eastern Kamchatka, the Kuril Islands to the north coast of Hokkaido, and then northward along west Kamchatka to the north coast of the Sea of Okhotsk. Some streams on the Komandorskiy Islands have small populations of sockeye salmon.

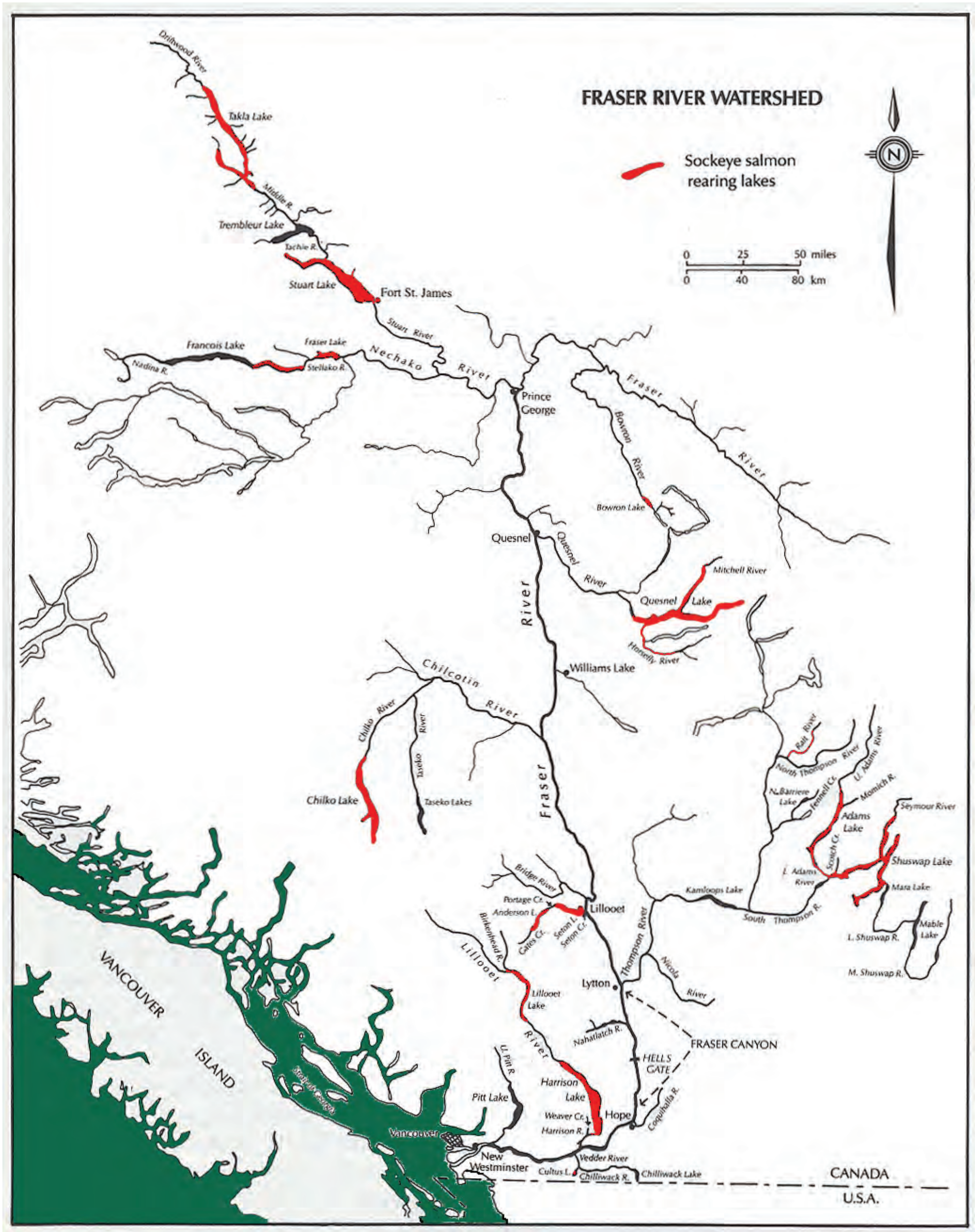

Fig. 3 Sockeye salmon nursery lakes in the Fraser River watershed.

In British Columbia, the Fraser, Skeena, Nass, and Somass river systems are significant sockeye salmon watersheds. About 40 unique populations of sockeye salmon spawn in 22 lakes in the Fraser River watershed (Fig. 3). Hereafter, one or more populations spawning in a specific lake will be referred to as a stock. The Adams River stock is generally considered the most abundant although on average, the Chilko Lake stock has greater production because its abundance does not exhibit the large interannual swings in abundance found in the Adams River stock. Large sockeye salmon runs used to appear in Rivers and Smith inlets, where they spawn in tributaries of Owikeno and Long lakes, respectively. Despite their relatively small size, these two lakes had the highest production per unit area in the world. Great Central, Sprout, and Kennedy lakes are significant sockeye salmon nursery lakes along the west coast of Vancouver Island. In addition, there are many smaller lake systems supporting small sockeye populations.

1.5.2 Spawning behaviour

Spawning behaviour of sockeye salmon consists of a combination of nest building activities by the female and courtship displays by the male, leading to deposition of fertilized eggs in a nest. The female is the dominant partner in this process and interacts with both the gravel environment and the courting male in a specific sequence of activities. The activities include nest site selection, nest construction, courtship display, oviposition, fertilization, and closing of the nest. The female digs four to five separate nests in the gravel, one nest per day. Each nest contains several hundred eggs. After all the eggs have been deposited, the female covers all nests under a large gravel mount called a redd and defends the area against intruders. A few days after she has completed spawning, she dies and her body floats away with the current. This creates room on the spawning grounds for the next wave of ripe females to occupy nesting territories. The whole spawning process from moving onto the spawning grounds to death lasts about 10 days.

Unless indicated otherwise, throughout this report quantitative references to spawner abundance are *effective female spawners* rather than a total of males and females. The estimated numbers of female spawners has been reduced in consideration of the effects of pre-spawning mortality, female fecundity, and percentage of eggs laid.

Salmon eggs develop in the gravel during the winter where they are protected from floods, ice conditions, and predators. The rate of egg development during incubation is dependent on water temperature and genetic characteristics related to environmental conditions of the specific population. Embryonic development is faster as temperature increases. For example, a 1°C difference in average incubation temperature can change emergence timing by four weeks.

A true larval stage does not exist in salmonids. When 10–20% of the yolk has been utilized, the alevin, a larva with a yolk-sac attached to its belly, hatches from the egg for further development in the protective gravel environment. When the yolk-sac has been absorbed, the young salmon, now called fry, emerge from the gravel in spring during the early hours of darkness within a narrow seasonal time window. Incubation, emergence, migration, and spawning are coupled and related to stream temperature and timed so that emergence of fry across stocks coincides with the development of plankton blooms in rivers, lakes, and the ocean. Differences in incubation temperatures between river systems are compensated for by changes in timing of spawning and differences in embryonic development rates. Fish that breed in relatively warm streams generally spawn later in the season, whereas those that breed in relatively cold streams, spawn earlier. The emergence time of fry is the major evolutionary influence that establishes spawning time. Fry from inlet streams will proceed downstream to a nursery lake whereas fry from lake outlets move towards the shorelines of the river and require a period of growth before migrating upstream to the nursery lake.

1.5.3 Migrations and habitat changes

In the nursery lake most of the surviving juveniles rear for one year before making the physiological transformation that prepares them for the ocean. Their water type preference changes accordingly from freshwater to salt water and their colour changes from a yellowish brown fish with parr marks to one with silver sides and a greenish back. They are now called smolts and are ready to migrate downriver to the ocean.

Upon entering the Strait of Georgia most sockeye salmon smolts turn northward and migrate primarily along the mainland shoreline. They exit the Strait of Georgia through channels among the islands and continue their migration through Johnstone and Queen Charlotte straits towards the North Pacific Ocean where they enter south of Haida Gwaii (Queen Charlotte Islands). Upon entering the North Pacific Ocean the postsmolts migrate north and westward in band within 35 km off the coasts of British Columbia and Central Alaska until they reach the overwintering grounds south of Alaska during late autumn and early December.

During their ocean residence sockeye salmon move relative to the annual temperature cycle in the Subarctic North Pacific Ocean. They are in waters colder than 7°C in winter, 10.5°C in spring, and 15°C in summer.

Thus, they move south in spring and summer and north in autumn and winter. This migratory pattern is the reverse of birds which move north during spring and south in autumn during the changing seasons.

When sockeye salmon mature, they first migrate north from the ocean feeding grounds in late summer, then journey to the outlets of their home streams and rivers and continue to migrate upstream to their ancestral spawning grounds. The migration north and then towards the Fraser River is apparent from the changes in distribution of sockeye salmon captured and tagged in the North Pacific Ocean in April through August and recovered in fisheries that operate in the approach routes to the Fraser River around Vancouver Island.

Sockeye salmon enter the Strait of Georgia on their way to the Fraser River estuary by taking either the southern route via Juan de Fuca Strait or the northern route via Johnstone Strait. Up to 1977 about 80% of the sockeye salmon, on average, used the southern route. Thereafter, an increasing number (average 50%) of the Fraser River sockeye salmon entered the Strait of Georgia via the northern route. Although the cause of the change is not yet known, years of warmer sea surface temperature on the West coast of Vancouver Island resulted in more sockeye salmon using the northern route.

Upon reaching the Fraser River estuary, many sockeye salmon stocks continue their upstream journey to the spawning grounds (Fig. 3). Some, like the Adams River population, may hold for up to three weeks off the Fraser River mouth before commencing migration upstream. The life cycle is completed by spawning and deposition of the eggs in gravel beds, and then death.

Thus, during their life cycle Pacific sockeye occupy a variety (12) of habitats (Fig. 4). Each is like a bead in a chain linked together by migrations. Therefore, it is important that each habitat is in prime condition and that migration routes between them are not hindered or blocked or made unsuitable. Any weak or broken link will significantly affect production and survival of the salmon.

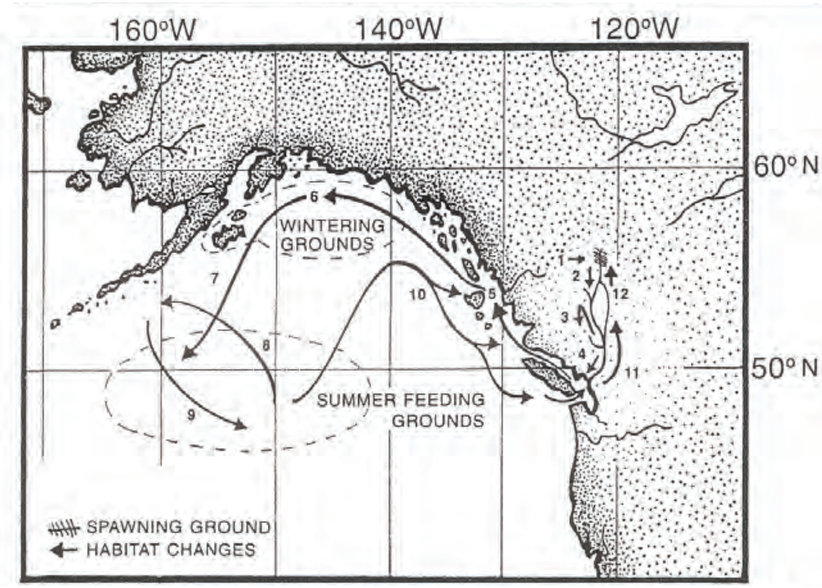

Fig. 4 Habitats occupied by a typical Fraser River sockeye salmon.

The long distance migrations of sockeye salmon from habitat to habitat provide some of the most enduring puzzles in salmon ecology. The migrations are well timed and well directed and can vary from a few hundred metres to thousands of kilometres. To perform these feats, sockeye salmon possess a remarkable set of direction-finding mechanisms that include sun compass and magnetic compass orientation. They are also able to distinguish water masses, such as between their natal tributary and nearby tributaries, and differences between stocks on the basis of odour.

Sockeye salmon are also able to migrate to a goal, such as the estuary of their natal stream, from any area in the North Pacific Ocean. This goal-finding ability is evident in the high rate of homing (>95%) to their ancestral spawning grounds. To quote Ferris Neave, a fisheries biologist who worked at the Pacific Biological Station in Nanaimo, British Columbia, for many years, "*It is difficult to avoid the conclusion that throughout the period of ocean life some awareness of position in relation to the place of origin is maintained*". The mechanisms underlying this capability are not well known, except that learning of the characteristics of the goal is involved.

Despite an understanding of the migratory patterns of sockeye salmon and some of the mechanisms involved in direction and position finding and water recognition, we are unable to predict accurately certain key events that are critical to the management of harvests. The least well known of these are properties associated with their life at sea.

1.5.4 Ecotypes

The strong tendency of sockeye salmon to return to their place of birth for spawning resulted in geographic and reproductive isolation that led to the development of many ecological forms during evolution. Differences can occur in many aspects of their biology, such as incubation period, age of seaward migration of juveniles, size of juveniles at a given age, ocean distribution, route and timing of migration shoreward, direction-finding abilities during migration, timing of stream entry, timing of spawning, fecundity, egg size and morphometric characteristics. These variations, which can vary both among, as well as within, stocks from region to region, are closely related to the ecosystems inhabited. There is sufficient evidence to conclude that many of the populations of sockeye salmon maintain such close associations with birthplace that they differ genetically from each other.

Many variations have developed in sockeye salmon upon the general pattern of movements between freshwater for rearing and reproduction and salt water habitats for feeding, by varying the duration of the juveniles in freshwater and of the immature in salt water from a few months to one or more years and by differences in timing of migratory patterns. Fry may move directly to salt water after emerging from the gravel; juveniles can spend two to three years in lake nursery areas before migrating to sea as smolts; maturing adults may return to their home river after one, two, or more years in the ocean; spawning can occur in inlet or outlet streams, along lake shores, or rivers. Also, the whole life cycle can be completed in freshwater, as in the case of kokanee. In total, sockeye salmon have about 18 different ecotypes.

Throughout this report, different ecotypes are identified by their age (x.y) where x = the number of complete winters (from fall through spring) spent rearing in freshwater after hatching, and y = number of winters spent at sea. The most common type in the Fraser River is age-1.2. Where age-1.x appears, for example, it refers to all fish that emigrated as one-year-old smolts, regardless how many years they spent at sea. Likewise age-2.x refers to all two-year-old smolts, without regard for their return year.

1.5.5 Production cycles

The majority of sockeye salmon in the Fraser River drainage system mature in their fourth year. A fixed age at maturity provides little opportunity for significant genetic exchange among cohorts. This has resulted in distinct reproductive lines between years in many stocks. The rigid four-year life cycle of Fraser River sockeye salmon has resulted in four reproductive lines. One of the lines often greatly exceeds the other three in abundance and is called the "dominant line". This phenomenon results in an imbalance in sockeye salmon population size in the Fraser River, producing a four-year cycle of abundance and catch. The dominant cycle often exceeds the others 100 to 1,000 fold.

In cases where strong cycles occur, elimination of a progeny line, by whatever cause, removes that line from the reproductive process and results in the loss of the genetic material of that particular year-class of a stock. Because of the inherited adaptations to the ecosystem, it may not be possible to easily restore lost populations of sockeye salmon in the event of natural or human-induced population failure. Many sockeye salmon stocks that disappeared from the Columbia and Fraser and other rivers never returned despite intensive restoration efforts.