The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River

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TECHNICAL REPORT 12

Fraser River Sockeye Habitat Use in the Lower Fraser and Strait of Georgia

Mark R.S. Johannes, Lee H. Nikl, Rob J.R. Hoogendoorn and Roxanne E. Scott

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Preface

Fraser River sockeye salmon are vitally important for Canadians. Aboriginal and non-Aboriginal communities depend on sockeye for their food, social, and ceremonial purposes; recreational pursuits; and livelihood needs. They are key components of freshwater and marine aquatic ecosystems. Events over the past century have shown that the Fraser sockeye resource is fragile and vulnerable to human impacts such as rock slides, industrial activities, climatic change, fisheries policies and fishing. Fraser sockeye are also subject to natural environmental variations and population cycles that strongly influence survival and production.

In 2009, the decline of sockeye salmon stocks in the Fraser River in British Columbia led to the closure of the fishery for the third consecutive year, despite favourable pre-season estimates of the number of sockeye salmon expected to return to the river. The 2009 return marked a steady decline that could be traced back two decades. In November 2009, the Governor General in Council appointed Justice Bruce Cohen as a Commissioner under Part I of the *Inquiries Act* to investigate this decline of sockeye salmon in the Fraser River. Although the two-decade decline in Fraser sockeye stocks has been steady and profound, in 2010 Fraser sockeye experienced an extraordinary rebound, demonstrating their capacity to produce at historic levels. The extreme year-to-year variability in Fraser sockeye returns bears directly on the scientific work of the Commission.

The scientific research work of the inquiry will inform the Commissioner of the role of relevant fisheries and ecosystem factors in the Fraser sockeye decline. Twelve scientific projects were undertaken, including:

Project	
1	Diseases and parasites
2	Effects of contaminants on Fraser River sockeye salmon
3	Fraser River freshwater ecology and status of sockeye Conservation Units
4	Marine ecology
5	Impacts of salmon farms on Fraser River sockeye salmon
6	Data synthesis and cumulative impact analysis
7	Fraser River sockeye fisheries harvesting and fisheries management
8	Effects of predators on Fraser River sockeye salmon
9	Effects of climate change on Fraser River sockeye salmon
10	Fraser River sockeye production dynamics
11	Fraser River sockeye salmon – status of DFO science and management
12	Sockeye habitat analysis in the Lower Fraser River and the Strait of Georgia

Experts were engaged to undertake the projects and to analyse the contribution of their topic area to the decline in Fraser sockeye production. The researchers' draft reports were peer-reviewed and were finalized in early 2011. Reviewer comments are appended to the present report, one of the reports in the Cohen Commission Technical Report Series.

Executive Summary

There is a general view that Fraser River sockeye face a series of challenges and issues which have influenced freshwater and marine sockeye growth and/or survival over at least the past two decades. The lower Fraser River and Strait of Georgia (also known as the Salish Sea) continue to be centres of human activity and development which have changed the natural landscape and potentially altered the extent and characteristics of sockeye habitats. Salmon are often viewed as a living barometer of the conditions in the environment and their habitat state and stock status could reflect potential impacts from human activities.

As part of the Cohen Commission's inquiry, a series of twelve technical reports have been developed to address potential issues identified during the first phase of the Commission's work as being possible causes of an observed long term decline in the production of Fraser River sockeye. The objective of these technical reports has been to explore causal hypotheses related to the observed declines. Within this context, the primary objective of the technical report presented here is to review and summarize potential human development-related impacts over the recent 1990 to 2010 period and to examine potential interactions between human development and activities in the lower Fraser River and Strait of Georgia and Fraser sockeye salmon habitats. Many of the issues and potential interactions between human development and their impacts summarized in this report could potentially apply to other species of wild salmon or other species of fish as well as their habitats; however, the evaluation of effects in this report is focused on Fraser sockeye.

The population of British Columbia has grown to more than 4 million people in 2005 (census data), with 3.2 million people living in urban areas concentrated around the lower Fraser River and the Strait of Georgia. Over the past century, land and resources have been developed and exploited throughout the lower mainland of BC (Fraser Valley and Fraser Delta areas) and the Strait of Georgia for housing, industry, infrastructure, transportation, forestry, agriculture and mining. Many of these activities are near or adjacent to the lower Fraser River and in urban and industrial centres along shorelines around the Strait of Georgia and thus have the potential to interact with the habitats used by sockeye. The Fraser River and the Strait of Georgia both have significant value for human use as commercial, recreation and transportation corridors and as receiving areas for wastewater, along with other human-related functions like water supplies, recreation, irrigation, and fisheries.

The factors used to examine changes in the level of human activities and or possible outcomes of those activities included: population (size, density), land use (agriculture, forestry), large industrial and infrastructure sites and projects, waste (liquid and solid waste), shipping vessel traffic, lower Fraser River dredging and diking, and the Strait of Georgia biological and physical water characteristics including non indigenous (invasive) species and human derived contaminants.

The approach and methods used to identify and define interactions and analyse their potential extent or overlap between human activity and sockeye habitats reflects a similar process to that used in environmental impact assessments.

Key Findings

Our review suggests that Fraser sockeye use specific or key life-history-related habitats with different residence periods (extent of habitat use over time), in both freshwater and marine areas of the lower Fraser and Strait of Georgia. The Strait of Georgia and the lower Fraser River are used by both juvenile and adult sockeye salmon as key habitats and migration corridors on their way to and from the North Pacific. While this may not be the case for some other Pacific salmon species, freshwater and marine habitats used by sockeye often have short residence periods (days); with the exception of incubation in freshwater spawning habitats and rearing in lakes (months to years). In the ocean, sockeye exhibit large annual and seasonal variation in spatial distribution dependent on marine water properties encountered and on preferred prey distribution and abundance. Results from other commission technical reports, our information review and examples from the literature suggest the annual variation in the quality of these conditions (water properties and biological characteristics) may have important links and potential effects on sockeye production. Juvenile sockeye in the Strait of Georgia appear to be particularly sensitive to changes in growth experienced during cool productive and warm unproductive conditions related to prey availability, surface currents and swimming speeds, and potentially to competitors and predators.

Human Activities, Habitat Interactions

Human development across the Georgia basin has seen large changes in population size and density in urban centres. Most of the population is centred in the lower mainland and south-eastern Vancouver Island with population size in most regional districts and municipalities in the lower mainland having increased by 150% over the past 20 years. Changes in population reflects increasing pressures on the environment because of the potential for higher levels of water use and pollution, nutrients and contaminants from wastewater and runoff, conversion of vegetated lands (natural, forests, agricultural) to urban and industrial areas. However, during that same time, programs have been in place to curb and manage runoff and human related discharges. Contaminants in the Strait of Georgia show a general improvement over time, with decreases associated with effluent regulation and improved treatment in recent years. For example, upgrades and efficiencies in the sewage collection and treatment systems in Metro Vancouver have taken place over the period of study. The physical construction of development projects adjacent to sockeye habitats has also been regulated over the period of study and there is evidence that habitat conservation efforts, through regulatory review and through restoration of previously impacted habitats, have resulted in habitat gains in the Fraser River estuary over the period of study for this report (1990 – 2010). However, some of the earlier habitat projects, carried out prior to the present period of study, were not successful at achieving "no net loss" of fish habitat. There is evidence that information learned from those projects has been incorporated into successful compensatory designs on contemporary projects in the Fraser estuary, underlining the importance of continued scientific learning regarding habitat ecology.

The Strait of Georgia and the lower Fraser River, support a large number of non-indigenous species (NIS), greater than twice the number found elsewhere on the Canada's West Coast. With the exception of intertidal benthos, the number of NIS in freshwater and marine environments have remained approximately stable from 1990 to 2010.

Increasing population size, urban density, industrial and infrastructure development and associated land use and waste as factors in the decline of Fraser sockeye were ranked as having low to moderate potential for impacts on juvenile and adult sockeye habitats in the lower Fraser River and adult sockeye habitats in the Fraser estuary. As a result of regulatory pressures and technological changes and despite population growth, solid waste, wastewater, contaminants and non indigenous species introductions appear to have remained mostly stable over the time covered by this review, in contrast to Fraser sockeye production which has declined. Changes in urban and rural land use have implications on increased sediment and erosion, nutrient, contaminant and stormwater runoff which could affect sockeye habitat use in the lower Fraser River, particularly in habitats used in locations off of the main channel. For instance, river-type sockeye will make use of the mouths of urban creeks or off-channel areas for rearing prior to migration to the Strait of Georgia. Stormwater and wastes deposited directly or inadvertently would cause direct exposure to sockeye, particularly in freshwater rearing habitats used by river-type sockeye. The proportion of river-type sockeye within the Fraser sockeye population is estimated to be less than 1%.

In many areas where human activities and development are concentrated, sockeye often have limited residence periods in adjacent habitats. For example, the lower Fraser River and estuary are primarily used by both adult and juvenile sockeye over periods of days as migratory corridors,with some exceptions. Historically (i.e., over the past century), many human activities may have had moderate to severe effects on sockeye habitats, but these impacts have not been generally observed during the last 2 decades and importantly, these impacts have not been observed to coincide with the decline of the Fraser River sockeye. The human activities often exhibited limited spatial and temporal (duration, timing) overlap with spatial and temporal sockeye habitat use. In a number of instances, additional regulatory controls (agricultural and forestry practices, shipping, ballast discharge, regulatory review of project development, non indigenous species introductions), improvements to industrial and municipal practices (solid and liquid waste management), and management regimes and protocols (urban development, agricultural and forestry practices, project development, dredging, dikes) have resulted in reduced or declining potential effects and reduced interactions and risk of loss or degradation of existing sockeye habitats relative to periods prior to the last two decades. There is room for continued improvement in a number of these areas.

This review is specific to sockeye and their habitat use and should not be extrapolated to interactions between human activities and other salmon and fish species' habitats.

Water properties (sea surface temperature, salinity, Fraser River discharge, prevailing winds on the sea surface) and biological conditions (plankton, fish) in the Strait of Georgia show a large range of variation over seasons and years. Potential interactions between biophysical conditions in the Strait of Georgia and sockeye (habitat and habitat use) have been inferred by our findings but limited existing studies and data prevent an adequate analysis of the extent of these interactions and, in particular, causal links cannot be established. Existing studies suggest that there may be an association between changes in biophysical conditions in the Strait of Georgia and the effects on sockeye habitat use, feeding and growth and potentially production. This expectation is not supported by conclusive results and statistical hypothesis tests, but is supported by studies which suggest that Fraser sockeye production is expected to be higher with increased sockeye growth and condition, relative to poorer sockeye production in years, seasons and habitats linked to lower growth and condition. Cooler years in the Strait of Georgia are expected to comprise habitats with higher abundance and availability of preferred (larger sized, higher energy content) sockeye prey and lower levels of competitors and predators. Relative to other human factors examined in our review, the changes and variability in the biophysical conditions associated with cool or warm water years can be widespread, extending over large areas of sockeye habitats and portions of life history for both juvenile and adult stages. In some seasons or years, changes in biophysical conditions and resulting sockeye preferred food availability can be expected to have profound positive or negative effects on sockeye growth and production.

Habitat Protection Strategies

The habitat protection strategies used in the lower Fraser River and Strait of Georgia, appear to be effective at supporting sockeye habitat conservation. More broadly, a hypothesis that the declines in Fraser River sockeye production over the period 1990 – 2009 are the result of habitat impacts from project development is not supported by the net habitat gains that have occurred over the 1990 – 2010 period.

The development of a project is required to provide compensatory fish habitat to offset project-related disturbances/impacts and often provides an opportunity for habitat gains. However, we also found evidence that habitat losses associated with project development had occurred prior to the period covered by our review. These losses were presumably the result of inadequate knowledge and experience in the design and construction of habitat compensation and / or indicate that the regulatory review process may not have been appropriately used. Therefore, maintaining active review of habitat projects may be a critical habitat management approach and potentially an important requirement for current and future activities and human development projects. Although the effectiveness of habitat compensation projects in the Fraser River appears to be improving, the need for an improved habitat science, monitoring and data management framework is clear and aspects of this need are consistent with recommendations made by others over the past decade or two. In our view, some efforts have been made in this direction, but these have not been adequate and are even less likely to be adequate into the future. Habitat compensation techniques relied upon over the past decade or two may not be effective in the next decade or two as physical space in urban centres for such compensation becomes more limited. Research in habitat ecology to evaluate alternative approaches to those prevailing today will be needed to adequately evaluate habitat compensation projects.

Programs and management initiatives used to examine and understand the quantitative parameters of habitats, potential losses and gains, habitat quality types and the dynamics of habitat productivity do not appear to be sufficient for keeping track of the current and future status of habitats used by sockeye and potential links and associations to variations in sockeye productivity. Habitat science, management, inventory and reporting should be brought together into an integrate framework as habitat compensation projects become more challenging and environments are more strongly influenced by changing climates and diminishing space in which to construct new habitats.

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Section 1: Introduction

Adult sockeye salmon (*Oncorhynchus nerka*) returning to spawn in the Fraser River have had declining numbers for the past 2 decades. The causes of these declines, relative to both forecast expectations of returning salmon and numbers of spawners, have been unclear but have led to fisheries harvest restrictions over this time period and, in 2007 to 2009, to closure of the sockeye fishery. In 2009 only 1.5 million adult sockeye returned to the Fraser River, the lowest number since 1947 and less than 15% of the preseason forecast expected returns. During approximately the past two decade period, the number of adult sockeye spawning in Fraser watersheds has increased and the proportion of catch relative to total returns has been reduced. Given that spawner numbers have increased, and catch has decreased, lower returns appear to be associated with reduced Fraser sockeye productivity (egg to returning adult survival) starting in the early 1990's to the present (Peterman et al. 2010). In contrast to this 20 year decline, sockeye returns in 2010 were high, representing the largest Fraser sockeye return since the early 1910s.

There is a general view that Fraser River sockeye face a series of challenges and issues which have influenced freshwater and marine sockeye growth and/or survival over at least the past two decades. The lower Fraser River and Strait of Georgia (also referred to as the "Salish Sea") continue to be centres of human activity and development which have changed the natural landscape and potentially altered the extent and characteristics of sockeye habitats.

Part of Commissioner Cohen's investigation is the review of the "*current state, predictions of future status and potential causes of the Fraser sockeye decline*". Based on public input, past reviews and recommendations, a number of suggested issues have been put forward as potential causative factors in relation to Fraser sockeye declines (Cohen 2010) including:

- Sockeye fishery and habitat management and conservation;
- Organization and structure of agencies;
- Aboriginal law;
- Policy and regulatory structure;
- Harvest management and harvesting;
- Enforcement;
- Population dynamics;
- Habitat enhancement and restoration;
- Protection of sockeye biodiversity;
- Watershed and marine coastal planning;
- Effects on habitat in the Fraser River watershed;
- Predation;
- Diseases, viruses, bacteria, and parasites;
- Salmon farms;
- Effects on habitat in the marine environment.

As part of the commission's investigation, a series of twelve technical reports have been developed to address the issues outlined above and to explore causal hypotheses (Peterman et al. 2010) related to the declines in Fraser sockeye returns. The primary objective of this Commission technical report is to review and summarize potential human development-related effects over the recent (1990 to 2010) period and to examine potential interactions between human development and activities in the lower Fraser River and Strait of Georgia and Fraser sockeye salmon habitats. The terms of reference for this report are presented in Appendix 1. Peer reviewer comments on an earlier draft report and the author's responses are presented in Appendix 2. Commission technical reports relating to the remaining issues have been assigned, under the Commission's investigation, to examine the cause and potential mechanisms associated with the decline of Fraser sockeye, including reviews on diseases and parasites, contaminants, marine processes, salmon farms, harvesting and management, climate change, and predators.

Pacific salmon in Canada are distributed throughout BC and the Yukon and represent thousands of populations (Foerster 1968, Groot and Margolis 1991, Riddell 2004, Augerot 2005, Labelle 2009, Johannes 2011). Wild salmon are an icon in our past and present society and culture, and remain a resilient and diverse species in nature. Salmon are viewed as a living barometer of the conditions in the environment and habitat state and stock status have been thought to reflect potential human-related impacts. Public interest and discussion on wild salmon and recently on Fraser sockeye has often focused on issues which affect, are perceived to affect or have potential to contribute to salmon survival and success. Many populations of salmon face declining numbers, reduced survival, loss of habitats through direct and in some cases undefined impacts from multiple human and natural sources including water and land development, population growth, habitat disturbance and destruction, and more global issues including climate change and variation (Lichatowich 1999, Montgomery 2003). Many of the issues and potential interactions between human development and their impacts, as summarized in this report, could potentially apply to other species of wild salmon, depending on the habitat use and life histories of those species and how these interact with different aspects of human development and activities. Certain species could be affected to greater or lesser degrees than sockeye. This technical report, however, is a compilation, analysis and summary of available information to document the status and current issues between Fraser sockeye salmon habitats and potential impacts from human activities.

Background

The population of British Columbia has grown from approximately 55,000 in 1850, to over one million in 1960, and to more than 4 million people in 2005, with 3.2 million people living in urban areas concentrated around the lower Fraser River and the Strait of Georgia. Over the past century, land and resources have been developed and exploited throughout the lower mainland of BC (Fraser Valley and Delta) and the Strait of Georgia for housing, industry, infrastructure, transportation, forestry, agriculture and mining. Many of these activities are near or adjacent to the lower Fraser

River and in urban and industrial centres along shorelines around the Strait of Georgia. The Fraser River and the Strait of Georgia both have significant value for human use as commercial, recreation and transportation corridors and as receiving areas for wastewater, along with other human-related functions like water supplies (e.g., drinking, industrial), recreation, irrigation, and fisheries.

As the number of people living on the periphery of salmon habitats has increased, pressure on the environment and on natural resources has also increased through urban and industrial development, land and resource use, and enhanced point source and non point source effects on the quantity and quality of salmon habitats. There are multiple interacting human activities and developments which could influence and potentially negatively impact Fraser sockeye survival throughout the various life history stages and the habitats they encounter. Evaluating how these factors interact with sockeye habitats is a focus of this report.

Approach

Our review and analysis involved compiling available data from various technical reports, primary literature and online sources of potential factors or measures related to human development and activities in the lower Fraser and Strait of Georgia. A statistical analysis of the association of human activity and potential impacts on sockeye habitats and, in turn, on Fraser sockeye productivity was not possible in this review due to the limits on the nature and extent of data available for human activity and in particular the lack of quantitative information on sockeye habitats. The approach used to identify and define interactions and analyse their potential extent between human activity and sockeye habitats reflects a similar process to that used in environmental impact assessments. This approach identifies potential interactions as: (a) likely interaction, (b) limited interaction and (c) no interaction. Information from relevant literature was compiled and mapped and used to identify the extent of the potential interactions between human development and key sockeye habitats. An ordinal rank was applied to classify the level of interaction between factors used to express changes in human activities and the potential for loss or degradation of key sockeye habitats in the lower Fraser River and Strait of Georgia. The level of significance of the potential interaction was evaluated and assigned based on criteria adopted from definitions provided in the Canadian Environmental Assessment Agency's reference guide (i.e., FEARO 1994) including:

- Extent of the geographic area of human activities and their overlap with key sockeye habitat;
- Magnitude or severity of human activities impact on key sockeye habitats; and,
- Duration of effects and overlap (human activities and sockeye habitat use and period of residence).

The factors used to express changes in human activities reflected those factors identified by Cohen (2010) and, with specific focus of the present study, included: population (size, density), land use (agriculture, forestry), large industrial and infrastructure sites and projects, waste (liquid and solid waste), shipping vessel traffic, lower Fraser River dredging and diking, and the Strait of Georgia biological and physical water characteristics including non indigenous (invasive) species and contaminants . The factors selected for this study are also comparable with similar factors examined in BC's 2006 State of the Environment report (MOE 2006a,b,c,d) and in other ecosystem status reports for the Strait of Georgia (Wilson et al. 1994, Hatfield 1996, Johannessen and McCarter 2010).

An approach reliant on quantitative measures of changes in sockeye habitats was not possible for this report due to the lack of quantitative data available on the extent and quality of sockeye habitats across the lower Fraser River area, lower Fraser watersheds (Harrison, Chilliwack and Pitt Rivers) and the Strait of Georgia. However, some estimates of habitat gains and losses have been developed, where possible, for subsets of sockeye and fish habitats. A review was also conducted to identify sockeye habitats and classify key habitats based on reported extent (space and time) of habitat use by life history stage. The review for known information on sockeye habitats and habitat use included unpublished and published technical reports and primary publications, Fisheries and Ocean Canada's (DFO) Salmon Escapement Data System (SEDS) and Stream Catalogues, and review of records available for the area in the Fisheries Information Summary System (FISS).

The material in this report was developed to summarize:

- The extent of sockeye habitats and habitat use in the lower Fraser River and the Strait of Georgia;
- Human development and activities;
- Potential interactions and suspected consequences of human development and sockeye and sockeye habitats over the 20 period of decline; and
- Existing sockeye habitat conservation and protection strategies.

The material in this report was organized into three separate sections considered individually:

- Sockeye habitat and habitat use (Section 2);
- Factors of human activity and development (Section 3); and
- Interactions and consequences of human activities on sockeye habitats (Section 4).

Section 2 provides a review of sockeye habitat use and distribution across life history stages in the lower Fraser River and Strait of Georgia as identified from the sources noted. It was beyond the scope of this review to obtain unpublished experience from the private and public sector biologists who have worked in the Fraser River and Strait of Georgia ecosystems or to survey traditional ecological knowledge held by First Nations in this area. While these sources would undoubtedly add to the knowledge base, we believe that the description of sockeye habitat use presented here addresses the dominant habitat uses, appropriate to the present scale of enquiry. This section of the report presents a conceptual understanding of key sockeye habitats, habitat use and feeding areas and integrates other models and reviews presented in the literature (i.e., Barber 1979, 1983, Groot and Cooke 1987, Crittenden 1994, Peterman *et al*. 1994, and Levy and Cadenhead 1995).

Section 3 is a summary of results for factors used to express changes over space and time in human activities in the lower Fraser River and Strait of Georgia. This section of the report is a compilation of multiple factors used to define human activities and development issues which may overlap and interact with sockeye habitat use. Results were presented across a series of maps to illustrate issues associated with time and space. It was not possible to describe every issue associated with human development and specific factors were chosen to express patterns and trends which might have an effect on sockeye and their habitats.

Section 4 is a summary and interpretation of potential interactions between human activities and sockeye habitats and inference of potential effects on Fraser sockeye production, specifically with regard to the 1990-2009 decline. This section also expands on existing salmon habitat protection strategies and identifies key findings and recommendations.

This report presents information on observations and issues of human activity, and records of observation and distribution for sockeye salmon in the lower Fraser River and Strait of Georgia but does not include a review relevant for all wild salmon species in these areas. This overview is specific to Fraser River sockeye salmon; however, we note that certain human activities and impacts that may not interact with sockeye habitats could interact with habitats used by other fish such as sturgeon or by other salmon species. We caution that a finding, for example, that sockeye are not likely to be affected by a given human activity should not necessarily be taken to imply that the activity is ecologically benign across all species. The present review is not suitable for broad extrapolation to other salmon or fish species and habitats. Our report does not include review of the effects of climate change, disease and parasites, predation, contaminants and other topics considered in the various technical reports to the commission of inquiry.

Methods and Data sources

Data Sources

Information on sockeye habitats and human development for the lower Fraser River and Strait of Georgia was compiled from available sources, existing databases and inventories, data and technical reports and from primary literature. Data on sea surface temperature and chlorophyll in the Strait of Georgia was also generated for this report through analysis and interpretation of satellite imagery. Sources and citations for data and information used are provided with each set of results. Results are presented through thirty-six 11" x 17" map series to present both spatial and temporal information for this report.

Spatial and temporal data compiled for this report include:

a) Distribution of sockeye in the lower Fraser River and Strait of Georgia based on database records, existing observations, catch records, reports and primary literature;

b) Human population and business statistics from Canadian population, agriculture, business census records for population, agricultural land use by regional district, solid waste disposal, and shipping activity;

c) Forest harvesting activities in south coast Timber Supply Areas and Vegetation Resource Inventory database harvest areas over time in crown lands;

d) Large industrial and public sites and projects in the lower Fraser River corridor and Strait of Georgia based on BC's major project inventory, Environmental Assessment Office project registry (Canadian and BC) and review of map and satellite based information to define historic and recent industrial and infrastructure sites;

e) Liquid waste discharge from Metro Vancouver wastewater treatment facilities in the lower Mainland area including plants at: Lions Gate, Iona Island, Lulu Island, Annacis Island, Northwest Langley from Metro Vancouver Liquid Waste Management Plans;

f) Lower Fraser River navigational channels, dredging and disposal of Fraser River sand at sea based on Port Metro Vancouver records, primary literature and Fraser River Estuary Management Program reports and records;

g) Extent and distribution of dikes in the lower Fraser River from Fraser River Flood Control Program mapping, reports and primary literature;

h) Primary generated data from remote sensing (satellite imagery) on spatial and temporal trends in sea surface temperature (SST) and chlorophyll (Chl *a*) in three sub-areas within the Strait of

Georgia (Juan de Fuca Strait, southern and northern Strait of Georgia) for months from April to September in years 2001-2010 for SST and 1998-2010 for Chl *a*;

i) Water properties and phytoplankton characteristics in the Strait of Georgia including Fraser River discharge, sea surface temperature and salinity from lighthouse ocean data, online wind data, data and technical reports and primary literature;

j) Biological properties and characteristics in the Strait of Georgia including zooplankton characteristics, and small fish (planktivore) including herring abundance from existing data records and assessment programs within Fisheries and Oceans Canada, online data sources and technical reports and primary literature;

k) Contaminant characteristics in sediments, and the ecosystem in the Strait of Georgia based on primary literature, data reports, and BC State of the Environment reporting (MOE 2006, a, b, c, d); and

l) Non indigenous species introductions in the lower Fraser and Strait of Georgia derived from technical reports and primary literature.

In some cases, historic information for a specific factor was not available for the entire twenty year period of interest, or was not able to be compiled for analysis during the reporting time frame. A future review of this material could benefit from additional analysis of a number of potential factors of human development which are often considered in analyses of watershed disturbance consistent with program like Fisheries and Oceans Canada Wild Salmon Policy in BC (i.e., Stalberg et al. 2009) including: total land cover alterations, road density, water extraction, riparian disturbance, permitted waste management discharges and suspended sediment.

Literature, reports and data were compiled for this summary and analysis using key word and key phrase searches on Fraser sockeye distribution and habitat use, human development, activities and projects in the lower Fraser River and Strait of Georgia from journal articles, technical and data reports, observation records and databases (e.g., Web of Science, Fisheries and Oceans Canada WAVES Library System, FISS, SEDS, Beamish et al. 2003). Information sources were also developed from and compared against BC's State of the Environment reporting (MOE 2006 a, b, c, d), Fisheries and Oceans Canada State of the Ocean Reporting (DFO 2009, 2010, Irvine and Crawford 2008, Crawford and Irvine 2009, 2010), and ecosystem status reports for the study area (i.e., Levings et al. 1992, Wilson et al. 1994, Hatfield 1996, Fraser et al. 2006, Johannessen and Macdonald 2009, Johannessen and McCarter 2010).

Primary data sources for observations of sockeye habitats and distribution were obtained through review of data and survey reports from 1950 to present. In some instances general catch records were provided in primary literature; these could not be translated into specific areas or locations to help assign level of habitat use. Catch and observation records in the FISS and SEDS were reviewed as were data sources provided in maps supporting information on sockeye distribution and spatial and temporal habitat use. FISS records across the lower Fraser River watershed, and Strait of Georgia were reviewed and downloaded from an online database[1]. SEDS records were available in a number of reports and through assistance provided by DFO staff. As noted earlier in the report, we did not compile unpublished local ecological knowledge or traditional ecological knowledge on sockeye distribution and habitat use for this report.

Factors and data used to express changes in human activities development were derived from Stats Canada population, agriculture and business census data for 1985 to 2005 census periods. Individual data sets on wastewater, dredging, diking, large and major projects were derived from specific searches through: (a) online major projects inventory in BC, (b) Canadian Environmental Assessment (CEA) Agency and BC Environmental Assessment Office (BC EAO) project registries, (c) compilations and reports (Thompson et al. 2009), (d) review of online sources from Metro Vancouver, and (e) mapping and imagery to locate specific industrial sites and areas across the lower Fraser and Strait of Georgia.

Interactions between Human Development and Sockeye Habitats

Our review and analysis evaluated available data from technical reports, primary literature, online sources and generated some primary data (satellite imagery based SST, Chl *a*) on factors or measures that could be related to human development and activities in the lower Fraser and Strait of Georgia. A statistical analysis approach was not possible in this review due to the limits on the extent of quantitative data available for human activities and in particular the lack of quantitative information on sockeye habitats.

The approach used in our review to identify and define the extent of interactions and overlap between human activities and sockeye habitats reflects a similar analytical approach applied for effects assessments in environmental reviews of projects. Professional judgement of the review team and information from relevant literature was used to rank the extent of the space and time interaction and overlap for each factor used to express changes in human development / activity relative to the area and timing of sockeye habitat use.

Human activities and our results were organized into ten general factors to evaluate the level of interaction and overlap with sockeye habitats to evaluate potential risk of loss or degradation of habitats including:

1. Population (Population Size, Urban Centres)
2. Land use (Agriculture / Forestry)

[1] http://www.env.gov.bc.ca/fish/fiss/index.html

3. Large Industrial and Infrastructure Projects
4. Waste (Liquid / Solid)
5. Shipping and Vessel Traffic
6. Dredging, Diking, Disposal at Sea
7. Strait of Georgia Water Properties (SST, SSS, Fraser Discharge, Winds)
8. Strait of Georgia Biological Properties (Phytoplankton, Zooplankton, Planktivores)
9. Contaminated Materials
10. Non Indigenous Species Introductions

A hierarchical method was used to first classify and then rank the extent of interaction and overlap between human activities, expressed as ten general factors, and sockeye habitats.

First, we classified the potential extent of the interaction and overlap as: ● - likely interaction, ○ - limited interaction or n/a - no interaction. Where no interaction is noted, the classification means that an interaction is not likely and may not be considered significant. This classification is not intended to mean that there is no interaction in an absolute sense.

Second, we evaluated the level of significance for a likely interaction applied through a ranking scheme of nil, low, moderate and high levels of interaction across six general habitat areas in the lower Fraser River and Strait of Georgia to help differentiate adult and juvenile sockeye habitats and potential risks associated with human activities. The significance ranking was assigned based on the extent of interaction and overlap and the past, current or future risk of loss or degradation of key sockeye habitats. This ranking was assigned based on use of criteria adopted from definitions provided in the Canadian Environmental Assessment Agency's reference guide (FEARO 1994) including:

- Extent of geographic area of human development effect and overlap with key sockeye habitat;
- Magnitude or severity of human development effect on key sockeye habitats; and,
- Duration of effects exposure and overlap (human development / activity and sockeye habitat use and period of residence).

A summary rank was derived for each habitat area and factor interaction based on level of significance and expressed as risk of loss or degradation of adult and juvenile sockeye habitats associated with the effects of human development. The summary rank was derived following consideration of the level of significance expressed across interaction criteria for each human activity factor. Professional judgement was used to review final summary ranks to extent of the space and time interaction and overlap for each human activity factor relative the area and timing sockeye habitat use. Potential interactions between human activity and issues linking changes in sockeye habitats and Fraser sockeye production were summarized based on our results. A quantitative analysis (e.g., statistical analysis) was not a viable approach given the lack of available quantitative data on sockeye habitats and relationship to sockeye production.

Section 2: Fraser Sockeye Habitat Use - Lower Fraser River and Strait of Georgia

Sockeye Habitat Use

Observations of habitats and habitat use for juvenile and adult sockeye were compiled and mapped (Map 3, 4; Appendix 3) based on data, reports of known distribution and residence period (extent of habitat use over time) from existing literature, site specific catch or monitoring data reports and available georeferenced or map-based spatial information on sites and locations. Key habitats and habitat use were ranked as nil, low, medium (med) or high habitat use based on observed and documented habitat use for a given area. Observation of habitat use were derived from examining the relative abundance or catch and anecdotal information reported by authors on extent of habitat use across specific spatial locations for juvenile (Map 3-A-i; B-i; C-i) and adult (Map 3-A-ii; B-ii; C-ii; 3-D) sockeye. Report and data references are detailed on each map sheet.

Sockeye habitat use, residence period, and data source citations are compiled and presented in the following map results and detailed in Appendix 3:

- Map 3: Overview map of sockeye habitats in the lower Fraser River and Strait of Georgia;
- Map 3-A-i: Juvenile sockeye habitats in the Lillooet and Birkenhead;
- Map 3-A-ii: Adult and juvenile habitats in the Lillooet and Birkenhead;
- Map 3-B-i: Juvenile sockeye habitats in the lower Fraser River (Harrison, Pitt, Chilliwack);
- Map 3-B-ii: Adult and juvenile habitats in the lower Fraser River (Harrison, Pitt, Chilliwack);
- Map 3-C-i: Juvenile habitat in the lower Fraser River and Strait of Georgia;
- Map 3-C-ii: Adult and juvenile habitat in the lower Fraser River and Strait of Georgia;
- Map 3-D: Adult habitats in the lower Fraser River and Strait of Georgia;
- Map 4-A: Summary juvenile sockeye habitat use and migration in the Lower Fraser River and Strait of Georgia during warmer climate and low productivity years; and,
- Map 4-B: Summary juvenile sockeye micro-habitat use and migration in the Lower Fraser River and Strait of Georgia during cool – high productivity years.

Sockeye are distributed throughout much of the lower Fraser River (Schubert and Houtman 2007) and connected watersheds and throughout portions of the Strait of Georgia. Key sockeye habitats (Appendix 3) include:

- Freshwater – Harrison, Chilliwack and Pitt Lake watersheds used as spawning, incubation, rearing, smolt migration, and adult migration habitats including key spawning and rearing areas in the Birkenhead River, Lillooet Lake, Harrison Lake, Trout Lake Creek, Douglas Creek, Big Silver Creek, Weaver Channel and Creek, Chilliwack Lake, Cultus Lake, Pitt Lake (Upper Pitt River and Widgeon Creek - Slough);
- Freshwater – lower Fraser River above the tidal area (approximately at the Mission Bridge), used for rearing by 0+ river-type fry, smolt migration and adult migration including key rearing areas in the lower Harrison River, gravel reaches (Ellis et al. 2004) of the lower Fraser River, various sloughs and off channel areas downstream of the Harrison River;
- Tidal – lower Fraser River used as smolt and adult migration habitats; and,
- Marine – Fraser River plume, Strait of Georgia and Juan De Fuca Strait used as post smolt migration habitat for 1+ smolts, adult migration routes and holding areas, and 0+ post smolt rearing habitats and migration routes.

Sockeye salmon freshwater distribution in the Lower Fraser River, from Hope to the Fraser River estuary, extends to 4 major watersheds including Harrison and Lillooet, Chilliwack, and Pitt Rivers (Map 3, Appendix 3). Sockeye distribution within these watersheds extends to distinct sub-catchments which include key and some minor spawning and rearing lake habitats.

Sockeye habitats in the Harrison, Chilliwack and Pitt watersheds are used for a residence period of 4 to 6 months by river-type sockeye (Harrison), and for 1 or 2 years by lake-type sockeye and for spawning, incubation and juvenile nursery rearing in Lillooet, Harrison, Chilliwack, Cultus and Pitt Lake areas (Appendix 3, Map 3-A-i, ii; 3-B-i, ii; 3-C-i, ii). The 160 km portion of the lower Fraser River and estuary is used as a migratory pathway for smolts and adults with a residence period of often less than 7 to 10 days.

River-type sockeye aged 0+ originating from Harrison Lake use various sloughs and off channel areas in the lower Fraser River above the tidal area, for rearing for a period of 2 to 6 months (Appendix 3, Map 3-B-i). The Harrison river-type sockeye fry are small sized and migrate slowly out of the Fraser River and estuary across the Strait of Georgia to use rearing habitats around the southern Gulf Islands for a residence period of 4 to 6 months. Harrison river-type sockeye juveniles were observed in the Juan De Fuca Strait and west coast of Vancouver Island in February through June, 1 year after emergence.

Larger sized sockeye post smolts (juveniles) from the mixed Fraser stock (all upstream sockeye stocks) have a low residence period (< 2 days) throughout the Fraser estuary and use a northern migration route through the Strait of Georgia (to Queen Charlotte Sound (Irvine et al. 2010) ranging from 20 to 30 km / day in travel speeds (Appendix 3, Map 3-C-i). Specific eastern (preferred) and western migration routes and residence periods in specific habitats vary based on swimming speed, sockeye size, prevailing winds, surface currents, heterogeneity of plankton prey (Preikshot et al. 2010) and general cool / warm biophysical characteristics of the Strait of Georgia (Map 4-A, B). The residence period across the Strait of Georgia ranges from April to September with peak migration timing in May and early June (Appendix 3).

Adult sockeye use two alternative migration routes through the Strait of Georgia including a southern route through Juan De Fuca Strait with holding areas above the southern Gulf Islands and Fraser plume and estuary, and a second northern diversion route through Johnstone Strait and Discovery Passage along a western route in the Strait of Georgia to holding areas in the Fraser plume and estuary (Map 3-D) (Gilhousen 1960, Hamilton 1985, Groot and Cooke 1987, Blackbourn 1987, Groot and Quinn 1987, Woodey 1987, Thomson et al. 1992, Levy and Cadenhead 1995, McKinnell et al. 1999, English et al. 2004, Crossin et al. 2004, Hinch et al. 2005). Migration residence periods for an individual migrating adult are often less than 1 month (40 km/ day) (Quinn and Harter 1987) in the Strait of Georgia and lower Fraser River dependent on ocean currents (Thomson et al. 1992), during June to September of each year (Hamilton 1985, Woodey 1987). The lower Fraser River is primarily used as a migration corridor for all upstream and lower Fraser River sockeye stocks as passage from the ocean to natal streams of origin.

Sockeye Feeding in the lower Fraser and Strait of Georgia

The extent of different prey organisms consumed by Fraser sockeye entering the Strait of Georgia is relatively diverse, although less variable than pink, Chinook, or coho salmon (LeBrasseur 1965, 1966, LeBrasseur et al. 1969, LeBrasseur and Doidge 1966a, b, c, d, Foerster 1968, Beacham 1986, i.e., Daly et al. 2009). Sockeye are known to substitute other prey organisms if preferred prey are less abundant in a given year or season (Preikshot 2010, i.e., Karpendo et al. 1998, Tyler et al. 2001). Beacham (1986) observed little variability in diet between different sized sockeye in the Strait of Juan de Fuca. Sockeye diets in the Strait of Georgia and Juan de Fuca often comprise a number of major prey items and taxa including: euphausiids, decapods (crab larvae), hyperiid amphipods**,** copepods, Pacific sand lance (*Ammodytes hexapterus)* and other larval or small sized fish**.** Sockeye salmon are less piscivorous when compared to chum, coho and Chinook salmon, related to morphological differences among salmon species (sockeye have the largest number of gill rakers) (LeBrasseur 1965, 1966, LeBrasseur et al. 1969, LeBrasseur and Doidge 1966a, b, c, d, Foerster 1968, Beacham 1986).

Sockeye Key Habitat Use

Our review of existing information suggests that adult and juvenile sockeye use specific key micro-habitats in freshwater and marine areas of the lower Fraser and Strait of Georgia as depicted in Maps 4-A, B based on our observations presented in Appendix 3 and Maps in the 3 series. Migration routes in freshwater and marine habitats often have short residence periods. Freshwater spawning, incubation and lake nursery habitats have the longest residence periods. Freshwater habitats are most sensitive to environmental change (temperature, flow) and human disturbance (urban and industrial development, land and resource use and extraction) (i.e., Johannessen and Ross 2002) associated with smaller spatial scales for habitats (smaller areas) when compared to larger spatial extent of marine habitats. Freshwater habitats tend to be characterized by lower food supply and fewer predators, particularly during nursery rearing in lakes relative to marine habitats (c.f. Groot and Margolis 1991).

Sockeye habitat use in the lower Fraser River is primarily associated with migration through the central river thalweg at depths or river velocity (2 to 5 m), and quick passage associated with raising discharge from the Fraser River spring freshet. The large proportion of 1+ smolts from both the lower Fraser sockeye lake-type conservation units (Harrison, Chilliwack, Pitt) and the upper Fraser mixed sockeye stock, use the lower Fraser River and estuary as a migration corridor for entry into the Strait of Georgia. Sockeye migrations are in pulses of higher smolt numbers travelling down the river in large tight schools at higher levels of aggregation than are observed in nursery lakes. Smaller 0+ river-type Harrison sockeye fry appear to have an alternative strategy and use lower Fraser River sloughs and off channels above the tidal mixing areas of the Fraser, as nursery habitats for 4 to 6 months. Survey records show that sockeye smolts do not use the Fraser estuary for prolonged periods of residence as nursery habitats.

Key juvenile habitats in the Strait of Georgia are used as migration routes by schooling sockeye smolts. Sockeye appear to select micro-habitats associated with characteristics of northward flowing Strait of Georgia surface currents and eastern and western migration corridors around Texada Island oriented by prevailing winds and strong surface currents (0.5 km/hr) (i.e., Peterman et al. 1994). Sockeye temperature preferences are in the 10^{o}C range (c.f. Brett 1983, Welch et al. 1995, 1998) often within the upper 0 to 15 m of water column along the 100 m depth isobaths in the Strait of Georgia, away from shallow shoreline areas. Sockeye schooling and micro-habitat use are reflected in Strait of Georgia surveys which observe catches of low or alternatively very high numbers of juvenile sockeye, demonstrating a large range in spatial heterogeneity and distribution along migration corridors. Micro-habitat use appears to be associated with use of surface and tidal currents to assist migration and travel speed to find and feed on planktonic prey items (LeBrasseur 1965, 1966, LeBrasseur et al. 1969, LeBrasseur and Doidge 1966a, b, c, d, Beacham 1986; c.f. Karpenko et al. 1998, Tyler et al. 2001, Farely and Trudel 2009) which are often heterogeneously distributed (St. John et al. 1992, Campbell and Dower 2008).

The residence period in the Strait of Georgia, the level of spatial heterogeneity in distribution and potentially sockeye school size may be related to warmer or cooler conditions in the Strait of Georgia and the availability, productivity and distribution of planktonic prey (i.e., salmon distribution - Webb 1991, St. John et al. 1992; calanoid copepod abundance - El-Sabaawi et al. 2010; euphausiids and copepods – Mackas and Galbraith 2010 pers comm.). Salmon distribution during ocean migration has been linked to the distribution and characteristics of prey availability (Chuckukalo et al. 1995, Karpenko and Piskunova 1984, Davis et al. 2000, 2005, Preikshot et al. 2010). Sockeye schools may have a prolonged period of residence in the Strait of Georgia during years of favourable physical conditions and availability of prey (Map 4-B). If environmental and productivity (food supply) conditions appear sub optimal or limited in a particular year, sockeye schools migrate quickly through the Strait of Georgia to Queen Charlotte Sound (Map 4-A). In years of unfavourable environmental and productivity conditions in the Strait of Georgia, Fraser sockeye productivity (survival and growth) will also be sensitive to the conditions available in Queen Charlotte Sound (Irvine et al. 2010, McKinnell et al. 2011). Sockeye juvenile survival and growth can be constrained and is potentially sensitive to conditions available in the Strait of Georgia and to some extent Queen Charlotte Sound given the spatial limits of optimal habitats, water properties and the semi-enclosed nature of both habitats. Once sockeye migrate into the larger and more diverse North Pacific Ocean, they appear to have greater flexibility in habitat choice and feeding opportunities (Davis et al. 2005), but remain a strongly schooling, highly mobile, migratory and opportunistic planktivore.

This behavioural pattern is reflected in pulses of returning adult sockeye migrating through either the southern Juan De Fuca route, or more recently through the northern diversion route through Johnstone Strait. Adult habitat use in the southern or northern route is associated with Pacific Ocean currents and environmental conditions encountered during return migrations. Over the past 2 decades, the northern route has had an increasing proportion of adult sockeye relative to historic habitat use, although the southern route appears to be used by a larger proportion of Fraser sockeye. Adult sockeye school in holding areas at depth (where water temperatures are approximately 10^{o}C) off the Fraser River estuary, prior to migrating upstream to key spawning locations throughout the Fraser watershed. Sockeye populations and stocks consistently reflect a specific run timing for migration into the lower Fraser River and streams and lakes of origin. Adult sockeye hold at depth (10^{o}C) in loose aggregations in Harrison, Chilliwack, Cultus (Pon et al. 2010) and Pitt Lakes prior to spawning in October and November.

Summary of Sockeye Habitat Use

Sockeye use specific micro-habitats in freshwater and marine areas of the lower Fraser and Strait of Georgia. The Strait of Georgia and the lower Fraser River are used by both juvenile and adult sockeye salmon as key habitats, with short residence periods as migration corridors en route to and from the North Pacific. Feeding in the lower Fraser is likely to be in micro-habitats that are attached to the main channel but where water clarity is better (off-channel habitats) and where access to planktonic prey items may be better than available in the main channel. Disruptions or losses to these habitats may therefore have greater impact on sockeye than disruptions to the deeper portions of river bed (e.g., navigational dredging) because sockeye are not benthivores (bottom feeding). Sockeye exhibit large annual variation in spatial distribution dependent on water properties encountered and preferred prey distribution and abundance. Results suggest the annual variation in the quality of these habitats may have important links and potential effects on sockeye production. Juvenile sockeye in the Strait of Georgia appear to be particularly sensitive to changes in cool productive and warm unproductive conditions related to their growth and condition linked through prey availability, surface currents and swimming speeds, and potentially competitors and predators.

Section 3: Human development activities – Lower Fraser River and Strait of Georgia

Ten factors were chosen (below) and used as metrics to express changes over space and time in human activities and development in the lower Fraser River and Strait of Georgia (Map 1) during at least 1990 to 2010, including:

1. Population (Population Size, Urban Centres)
2. Land use (Agriculture / Forestry)
3. Large Industrial and Infrastructure Projects
4. Waste (Liquid / Solid)
5. Shipping and Vessel Traffic
6. Dredging, Diking, Disposal at Sea
7. Strait of Georgia Water Properties (SST, SSS, Fraser Discharge, Winds)
8. Strait of Georgia Biological Properties (Phytoplankton, Zooplankton, Planktivores)
9. Contaminated Materials
10. Non Indigenous Species Introductions

These factors were used as important characteristics and potentially stressors which could illustrate effects and interactions of human activities and development on the environment (MoE 2006a, b) and which show relevance for possible interaction with sockeye habitats. These factors were mapped to illustrate potential overlap and association over space and time with key sockeye habitats that were also mapped. The factors were spatially organized based on available data for regional districts and / or municipalities (Map 2) and point features as shown for the inventory of large industrial and infrastructure projects (Map 8) across the study area. In some instances information on certain factors were site and time specific (i.e., liquid waste, dredging).

Factors of Human Activities - Results

A summary of results for each factor are discussed in the following text. Detailed results are presented in a series of maps with narrative and data source for each factor. The interaction of these factors with sockeye habitats is presented in Section 4 of this report.

Results are presented in the following maps, including:

1. Population (Population Size, Density)
    - Map 5-A: Regional district population size and density;
    - Map 5-B: Municipal population size and density;
2. Land use (Agriculture / Forestry)
    - Map 6-A: Regional district agricultural land use and area;
    - Map 6-B: Regional district agricultural crop area and livestock
    - Map 6-C: Regional district agricultural land use practices and applications
    - Map 7-A: Forest timber volume
    - Map 7-B: Distribution of forest harvesting
3. Large Industrial and Infrastructure Sites and Projects
    - Map 8: Industrial and public projects, sites and infrastructure
4. Waste (Solid, Liquid)
    - Map 9-A: Solid waste
    - Map 9-B: Liquid waste from wastewater treatment plants in the lower Fraser River
5. Shipping and Vessel Traffic:
    - Map 10: Marine vessel traffic and tonnage
6. Dredging and Dikes
    - Map 11-A: Navigational channel, channel characteristics, dredging and disposal at sea
    - Map 11-B: Diking in the lower Fraser River
7. Strait of Georgia Water Properties - Sea Surface Temperature, Salinity, Prevailing Winds, Fraser Discharge
    - Map 12-A: Historic trends in water properties in the Strait of Georgia (sea surface temperature & salinity)
    - Map 12-B: Water properties across regions in the Strait of Georgia
8. Strait of Georgia Biological Properties - Phytoplankton and Higher Trophic Levels in the Strait of Georgia
    - Map 12-C: Phytoplankton and Zooplankton in Strait of Georgia
9. Contaminated Materials in the Strait of Georgia
    - Map 13-A: Water quality in the lower Fraser River and Strait of Georgia
    - Map 13-B: Contaminants in the lower Fraser River and Strait of Georgia
10. Non Indigenous Species Occurrence

- Map 14: Non indigenous species

1. Population (Size, Density)

Population size is a general factor used to express overall human activity and development related industrial, residential and agricultural land and resource use (MOE 2006a). Population size and density provide a broad metric of potential stress on the environment and allow a generic estimate of potential human activities that could result in changes in land and marine areas through urban, rural and industrial development. Trends in population size and density were derived from 1986, 1996 and 2006 national and provincial census data presented for regional districts and in Map 5-A and for municipalities in Map 5-B.

Most of the population in southern BC is distributed in the lower mainland of Vancouver and south-eastern portions of Vancouver Island. Human activities related to population size and density may affect sockeye habitats through direct habitat loss and through non-point source effects associated with changes in water quality and quantity. Population size and density, in most of regional districts and in all municipalities, increased by 150% over the past 20 years. Urban land areas in Vancouver have only increased 2.5% in the same time period (MOE 2006a), reflecting an increase in urban density (e.g., City of Vancouver). Urban areas and cities around the lower Fraser River comprise greater than 80% of the population in the study area. Cities like Surrey and Abbotsford showed the greatest level of growth within the study area.

2. Land Use (Agriculture, Forestry)

Development of residential, recreational, transportation and industrial lands in the lower Fraser and Strait of Georgia have removed and degraded habitat areas and natural environments over the past century (i.e., Fraser et al. 2006). Urban and industrial activities and development often lead to enhanced transportation land use and infrastructure projects creating larger built environments and impervious surface areas. Larger population size and density lead to higher levels of water pollution, nutrients and contaminants from wastewater and stormwater runoff. Reduced natural forest, riparian, wetland, watercourse and waterbody areas limit the natural capacity of landscapes to filter and buffer surface water runoff and recharge groundwater sources. Land use and area changes often are direct effects on water quality and quantity and indirect effects on fish habitats generally.

Agricultural (Map 6-A, 6-B, 6-C) and forestry land use (Map 7-A, B) have remained stable in many regional districts in the study area. Greater than 3000 ha of forest and agricultural land were lost and replaced in urban areas over the past two decades (MOE 2006a). The rate of urban growth through increased land area and use has slowed over the past two decades and has resulted in increased urban residential and population density in many communities.

Agricultural land area increased in the Fraser Valley associated with a high proportion of corn, and in the Lillooet Valley with a higher proportion of field crops and vegetables. Forest land use and timber volumes declined across all regions over the 20 year period. Reduced demand and timber volumes have led to pulp and paper mill closures in Elk Falls (2010) and Squamish – Woodfibre (2006).

3. Large Industrial and Infrastructure Sites and Projects

Large industrial and infrastructure sites and projects lead to greater land and resource use and increased levels of nutrients, sediment, and contaminants from wastewater and surface runoff (Map 8). More than 300 large industrial sites and infrastructure projects were constructed and operated in the lower Fraser River and Strait of Georgia during the past century. Approximately 70 projects were constructed and began operations from 1990 to 2010. A large number of these projects have limited, direct spatial overlap with sockeye habitats.

Approximately 36 private industry and public infrastructure sites or projects had potential overlap with aquatic habitats. Ferry and marine terminals, bridges, airports, smaller waste treatment plants (lower Fraser River), reservoirs and dams, aggregate pits were considered to have minimal overlap with sockeye habitats. The five pulp and paper mill operations (Howe Sound, Crofton, Nanaimo, Powell River, Elk Falls), and the Iona Island wastewater treatment plant were considered to have an overlap with sockeye habitats related to water and effluent discharge and the potential dilution zone around these projects. Wastewater treatment plants and pulp and paper mills were added into the inventory of large projects even though they were constructed and have operated for greater than 3 decades.

4. Waste (Solid, Liquid)

Larger areas and densities of human settlement and resulting residential and industrial land areas often lead to higher levels of solid (Map 9-A) and liquid waste (Map 9-B) disposal and discharge. The main sources of solid waste and wastewater are households, industrial and commercial operations and stormwater runoff.

The volume of solid waste disposed of per capita directly relates to the patterns of residential and industrial activities, development and consumption. Approximately 80% of marine pollution is estimated to be derived from land-based activities through liquid and solid waste (MOE 2006b). The waste sent to landfill is a potential source of nutrients and contamination for groundwater and/or surface water in older or poorly designed landfills. Landfills occupy large land areas and have become more difficult to accommodate in densely populated areas. Approximately 35% of municipal waste is generated by households, with the remainder from industrial sources (MOE 2006b). Programs to reduce the amount of solid waste disposed in favour of recycling waste, have been adopted in BC and Metro Vancouver for less than 20 years (Metro Vancouver 2010a). The provincial government has instituted a requirement for regional districts to plan and adopt solid and liquid waste management plans. Solid and liquid waste volumes did not increase across the region in response to population growth, due in part to improved best practices (recycling programs, secondary or better treatment), in all regions of the study over the past 20 years.

Wastewater is treated to protect human health and to reduce stress on the receiving environment. Wastewater is treated before discharge to the environment to remove some potential pollutants and to reduce the biological oxygen demand (BOD) and total suspended solids (TSS) (Metro Vancouver 2010b). The proportion of municipalities now using secondary and tertiary wastewater treatment have increased over the past 20 years (MOE 2006a,b, c) and has led to reduced tonnage of BOD and TSS discharged into the environment from municipal wastewater (Map 9-B), despite population growth during that time.

5. Shipping and Vessel Traffic

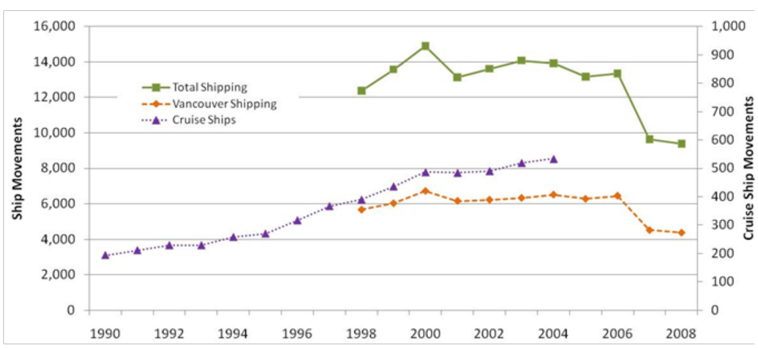

Figure 1. Ship movements in and out of ports within the Strait of Georgia and lower Fraser River area. *Source: Statistics Canada 2008, Shipping in Canada.*

Marine traffic is the main form of transportation for many goods and services across the coast. Shipping and marine vessels are viewed by some as a source of noise, contaminants, accidental spills and introduction of non indigenous species into marine areas of the Strait of Georgia through hull fouling and ballast water exchange (Levings et al. 2002, Larson et al. 2003, Levings et al. 2004, Richoux et al. 2006). Port vessel traffic (Map 10) across the Strait of Georgia remained generally stable during the past decade with some decline in ship movement and cargo tonnage in recent years associated with slower economic conditions (Figure 1). Cruise ship traffic has been projected to continue to rise over the next decade, although it remains a small proportion of total ship movements in the Strait of Georgia and Vancouver ports. Ferry traffic has remained stable throughout the past two decades. These results suggest that shipping and vessel traffic have limited direct interaction with sockeye habitats.

6. Dredging and Diking Activities

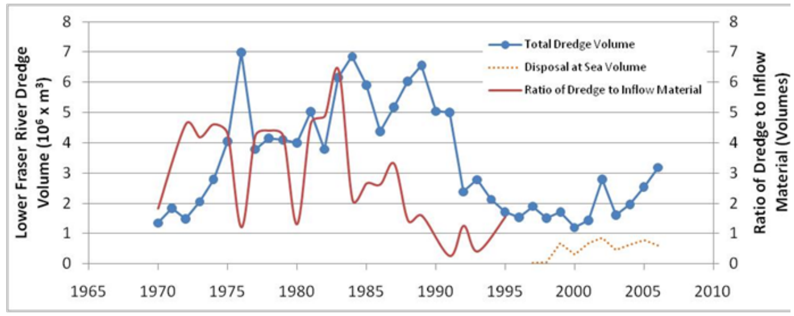

Figure 2. Sand dredge volume Ship movements in and out of ports within the Strait of Georgia and lower Fraser River area. *Source: Fraser River Estuary Management Program 2006.*

Dredging in the lower Fraser River below Mission has removed more sand and gravel river material than has moved into the lower river reaches over the past 3 decades (Map 11-A, Figure 2). Dredging has resulted in the south arm navigation channel bed elevation level being lowered by 3 m over a 30 year dredging period. The volume of dredged material removed from the river, however, has declined annually since the early 1990's (Figure 2). Specific seasonal dredging time windows have been instituted to manage dredging activities outside the residence period of migration for juvenile sockeye salmon in the lower Fraser River (FREMP 2006).

Fraser Valley urban areas and cities are protected by over 400 km of dikes between Hope and Sand Heads (Map 11-B). Extensive diking in the lower Fraser River was first initiated in early 1900's and largely completed by 1950. The early network of dikes has effectively removed many of the secondary and off channel areas of Fraser River gravel reach upstream and downstream of Chilliwack. No new dikes have been constructed in the past two decades although there have been upgrades to dikes during this time. Dikes are managed under the Fraser River Flood Control Program and are regularly maintained and upgraded where needed. In some instance dikes have been removed, or replaced to create opportunities for salmon habitat restoration (see *Insets 1— 3*).

7. Strait of Georgia Water Properties

The physical properties of marine water in the Strait of Georgia, including sea surface temperature (SST), sea surface salinity salinity (SSS) and nutrient properties and distribution, are determined through a combination of the Strait's physical bathymetry and dimensions (semi-enclosed sea), and energy from tidal mixing, currents, prevailing winds and freshwater input from the Fraser River. The strait is comprised of two shallow sills at the south (Victoria Sill, Boundary Pass) and north (Discovery Passage) ends (Map 1) which restrict water exchange and ocean upwelling from the Pacific Ocean through both the Juan de Fuca Strait and Johnston Strait (Waldichuk 1957, Davenne and Masson 2001). Water properties and circulation in the Strait of Georgia are primarily determined by the seasonality of freshwater discharge from the Fraser River, variation and strength of prevailing winds and strong tidal mixing and currents influence by climate and Pacific ocean conditions (Davenne and Masson 2001, Masson 2002). Freshwater discharge from the Fraser River controls local circulation and helps stratify the upper layers of the water column in the strait (Masson and Cummins 2007, Masson 2008, 2009). Stratification in the water column in the strait is primarily determined by seasonal changes in salinity associated with freshwater input (Masson and Cummins 2007, Masson 2009, Map 12-A) and not necessarily only by changes in sea surface temperature. Oxygen is produced in surface waters by mixing and the photosynthetic activity of phytoplankton. Oxygen at depth is generated by deep water renewal in late spring and late summer from the Pacific Ocean through the Juan de Fuca Strait (Masson 2002). The patterns of nutrient input for the main portions of the Strait are determined by seasonal Fraser River discharge and seasonal freshet derived from snowmelt in mid—late June and from coastal upwelling from the Pacific Ocean (Mackas and Harrison 1997). Increased seasonal runoff from the Fraser watershed supplies approximately 80% and 50% of the particulate and organic carbon loading respectively, delivered into the strait (Johannessen et al. 2003, Hill et al. 2008).

Based on these characteristics, seasonal patterns of temperature, mixing and currents driven in part by freshwater discharge and winds, determines the spatial distribution and physical habitat use of juvenile sockeye from June through August and adult sockeye from May to June (c.f. Groot and Cooke 1987, Peterman et al. 1994). Juvenile sockeye take advantage of the seasonality of surface currents for a northward migration through the strait, and the onset of seasonal increased spring planktonic prey abundance (Mackas et al. 2007, Haro-Garay and Soberanis 2008, Trudel et al. 2008, 2010, El-Sabaawi et al. 2010).

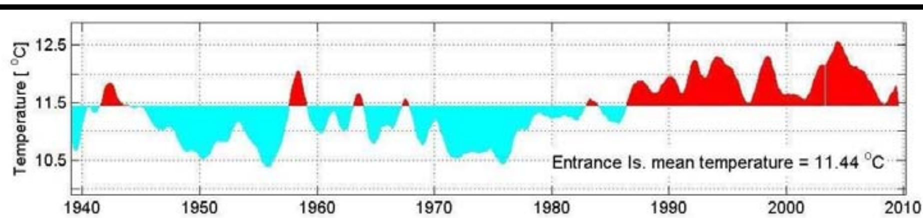

Figure 3. Long-term time series of monthly sea surface temperature anomalies from the long-term mean from 1936 – 2009 from Entrance Island, central Strait of Georgia, BC *(derived from Chandler 2010).*

Long-term time series of monthly temperature anomalies from Entrance Island lighthouse (Figure 3, Chandler 2010) relative to the long term average suggest that the period from the late 1980's to present experienced warmer conditions than those during the antecedent period from 1940. Similarly patterns of daily temperature from Chrome (northern strait) and Entrance Island lighthouses show a general trend in increased SST from 1980 to present (Map 12-A).

A time series of SST was generated from remote sensing (Map 12-B). The seasonal warming and cooling pattern was observed in the central and northern Strait of Georgia and Juan de Fuca Strait areas. SST in Juan de Fuca Strait was cooler at all time periods than the SST observed in the Strait of Georgia. The warmest seasonal temperatures were observed in August of each year with the warmest growing season during the 2001 to 2010 period occurring in 2007, and the coolest period occurring in 2008.

The physical changes observed represent a large spatial scale that overlaps extensively with Fraser sockeye habitat use. Changes in the physical water properties in the strait are linked to biological production which have combined implications on the distribution, growth and survival of sockeye.

8. Strait of Georgia Biological Properties

Water properties (sea surface temperature, salinity, Fraser discharge, prevailing winds) and biological conditions (plankton, fish) in the Strait of Georgia show a large range of variation over seasons and years (Map 12-C). Seasonal variation in primary productivity and phytoplankton abundance increases in the spring (Map 12-C) associated with available oceanic and Fraser River derived nutrients and with increased length of photoperiod; in summer phytoplankton are reduced in population associated with lower available nutrients and warmer conditions in the upper water column (Parsons et al. 1969a, Mackas and Harrison 1997, Pena 2008, 2010, Trudel et al. 2008). The depth of the euphotic zone (light penetration zone) and characteristics of near-surface stratification in part, controls the depth of water column available for phytoplankton growth. Chlorophyll *a*, a measure of the phytoplankton population, varies with season and varies spatially over the Strait with higher levels of Chl *a* in the south to lower levels in north of the Strait associated with the early summer Fraser River freshet (Yin et al. 1997), extent of the Fraser River plume, frequency and magnitude of storms, and the onset of longer summer photoperiod and greater solar radiation (Masson and Cummins 2007). Nutrients in the surface waters of the strait can rapidly change in association with storm driven winds, variation in the Fraser River discharge and uptake of those nutrients by phytoplankton (Pena 2008, 2010).

Phytoplankton primary production supports the marine ecosystem and food chain in the Strait (Parsons et al. 1969a, b). Primary production in the Strait is considered high relative to other coastal areas, but is spatially heterogeneous (Map 12-C) and often concentrated in areas of ocean mixing and the outlet of the Strait (Harrison et al. 1983, Yin et al. 1997a). The onset of the spring phytoplankton bloom in the Strait of Georgia ranges from late February to early April and appears to be associated with changes in wind, solar radiation (day length, cloud cover) and Fraser discharge (Allen et al. 2010) (Figure 4). It may also involve a series of blooms throughout the spring and summer (Gower and King 2010). Chlorophyll and phytoplankton data are limited over time, and associations to examine variations in zooplankton abundance in the strait are not supported with long term data.

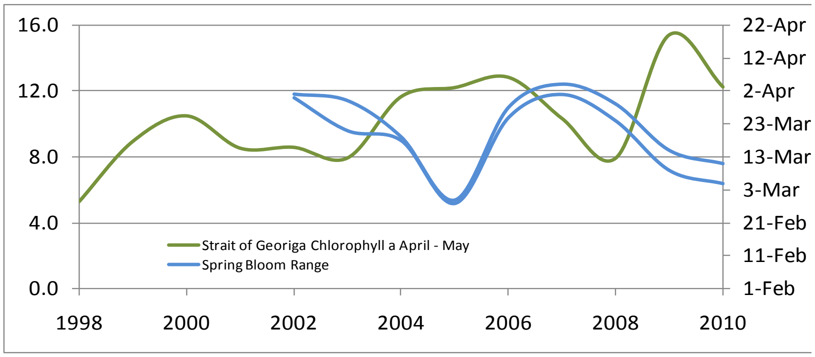

Figure 4: Spring chlorophyll a (April-May) derived from remote sensing satellite imagery (Map 12-C) and timing of spring phytoplankton bloom derived from modelling and data in Allen et al. (2010).

Changes to the distribution and abundance of the flagellate *Heterosigma* have been studied at a number of fish farms and nearshore coastal areas (Rensel et al. 2010). *Heterosigma* blooms around fish farms and enclosed inlets have been linked to fish and salmon mortality (Rensel 2007); however, fish kills from *Heterosigma* have also been recorded in Port Moody Arm where there are no fish farms (L. Nikl, *unpublished data*) and late summer conditions favour a *Heterosigma* bloom at the head of Port Moody Arm. Harmful *Heterosigma* blooms can potentially cause mortality to various marine species, including salmon, through altered ability to uptake oxygen and diminished respiratory function (c.f. Rensel et al. 2010). *Heterosigma* blooms and concentrations were monitored across the Strait of Georgia through the Harmful Algae Monitoring Program in a variety of nearshore coastal sites in the southern Strait of Georgia to Queen Charlotte Strait. Consistent with Rensel's suggestions about pink salmon distribution and migration patterns, and as discussed for sockeye salmon in Appendix 3 and Maps 3 to 4, sockeye salmon smolt distribution, timing and migration patterns tend to be outside nearshore coastal areas and time periods normally associated with the generation and spread of *Heterosigma* algal blooms. No observations are presently available to assert or reject causal links between sockeye mortality and harmful algal blooms. The major algal blooms observed in the southern strait during 1993, 1997, 2002, 2003, 2006, and 2007 coincided with warm less saline (June-July) years in the southern strait (Map 12-A) and were observed during seasons and years where highly variable phytoplankton and zooplankton concentrations were also observed (Map 12-C).

Zooplankton are the secondary producers and herbivores consuming phytoplankton in the marine food web. Zooplankton are a component of available preferred prey for Fraser sockeye while migrating through the Strait. Zooplankton in the Strait often have high concentrations around areas of tidal and water mass mixing and the Fraser estuary plume (St. John et al. 1982, Mackas et al. 2001), but are generally considered very patchy (spatially heterogeneous) in their distribution. *Neocalanus*, a calanoid copepod, has generally been considered the dominant zooplankton species in the strait and has been declining in abundance over the past decade or more (El-Sabaawi et al. 2009) (Figure 5). Total zooplankton population also appears to be declining across the strait (Map12-C) along with the duration and timing of peak zooplankton biomass in the spring, consistent with patterns in the Northeast Pacific (Batten and Mackas 2009, c.f. Johannessen and Macdonald 2009).

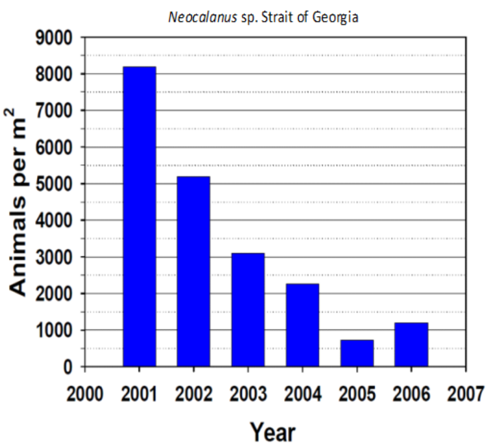

Figure 5: Declining *Neocalanus* abundance in the Strait of Georgia. Figure taken from Johannessen and Macdonald 2009, based on El-Sabaawi and Dower 2009, 2010, Campbell and Dower 2008, Sastri and Dower 2009, Batten and Mackas 2009.

Data from Mackas and Galbraith (pers. comm. 2010), who compiled available, albeit limited, zooplankton data although showed downward trends from 1990 to the present for spring season (log) biomass of large copepods (3-7 mm length), medium copepods (1-3 mm), and adult euphausiids in the Strait (Map 12-C). Although 2007 data were obtained with different sampling methods, they suggest that 2007 zooplankton abundance represented near low levels across already lower abundance during the past decade.

The timing and abundance of the zooplankton bloom in the strait may be related to changes in water temperatures, rather than just the concentration of phytoplankton food supply (Gardner 1977, Campbell and Dower 2008). Studies by Campbell and Dower (2008), Sastri and Dower (2009), El-Sabaawi et al. (2009, 2010) suggest that *Neocalanus* started a large decline in abundance in the 1990's, and a further decline starting in 2003 to low levels in 2007, associated with a warming trend over most of the coast and shelf areas near Vancouver Island and the Strait of Georgia. *Neocalanus* have not shown a sign of recovery in the recent period because of a warming trend in the strait throughout the water column in 2006 and 2007 (Campbell and Dower 2008).

Neocalanus is a sub arctic copepod and during warming conditions it is unable to complete its life cycle. Other copepods have become more abundant in the food web (Sastri and Dower 2009, i.e., *Metridia* and *Eucalanus*) with the decline of *Neocalanus*. Mackas et al. (2009) suggested that optimal cool high productive years showed a higher abundance of larger energy-rich sub-arctic copepods (i.e., *Neocalanus*) and chaetognaths. Warmer less productive years tended to be comprised of southern copepod (*Metridia*) and chaetognath species. As discussed in Section 2 of this report, sockeye are known to substitute other prey organisms if preferred prey are less abundant in a given year or season (Preikshot 2010). This shift in prey selection, however, may not be without food energy costs because *Neocalanus* have higher lipid content (El-Sabaawi et al. 2009)

Recent work has shown that a timing asynchronicity can occur if plankton prey have limited availability due to warming trends during sockeye smolt migration out of the Fraser River in early May to June (Yin *et al.*, 1997b, Beamish and Mahnken 2001, Beamish et al. 2004, 2010, Chittenden et al. 2010). As the timing of the zooplankton biomass peak occurs earlier in the season (Johannessen and Macdonald 2009), late migrating Fraser sockeye may have greater difficulty finding available prey.

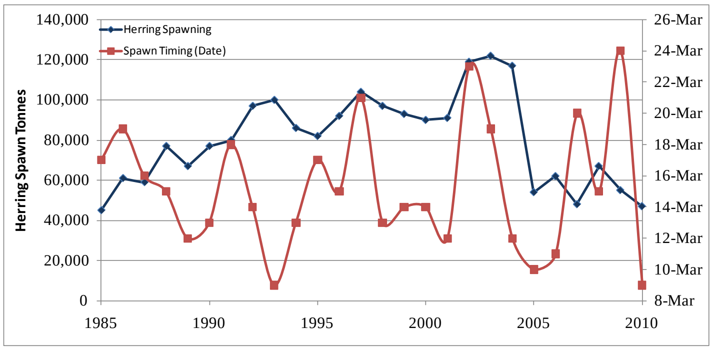

Figure 6: Pacific herring adult spawn biomass (tonnes) and herring spawning timing date. Data derived from Clearly et al. 2009

Pacific herring (*Clupea pallasi*) followed by Pacific hake (*Merluccius productus*) comprise the largest biomass of planktivore fish species that are potential competitors with sockeye for available prey in the Strait of Georgia. Herring and hake show large annual variations in abundance related to spawning success and recruitment (Hay et al. 2003, Schweigert and Haist, 2007, King and McFarlane 2006). These changes are often associated with climate driven changes in physical habitats. Most Strait of Georgia herring feed off the west coast of Vancouver Island during the summer months (Clearly et al. 2009, Schweigert and Clearly 2010). The herring population has continued to increase over the past two decades associated with changes in fisheries and peaked in 2004 (Figure 6). Hake monitoring in the Strait suggest that they are at stable levels of abundance.

Warming temperatures suggest decreasing food availability and/or quality which, together with shifts in behavior of Fraser sockeye outmigrants in response to changing physical characteristics of their marine environment, may limit their opportunities for increased growth and condition (related to ocean survival and adult returns) prior to moving offshore. The changes in temperatures and decreasing trends in *Neocalanus* coincide with the declines in the Fraser sockeye. However, the recent observations of the high 2010 Fraser sockeye returns is not consistent with that pattern. The Georgia Strait rearing year for the sockeye returning as adults in 2010 would have been 2008 and during 2008, the populations of zooplankton were higher than the previous year but not to an extent commensurate with the 2010 sockeye returns. Other factors, acting in combination are likely to be responsible for Fraser sockeye production.

9. Contaminated materials in the Strait of Georgia and the lower Fraser

Contaminants enter the Strait of Georgia through local discharges and long range transport. Urban and industrial activities and development in the strait have resulted in a history of contaminants (metals, organic pollutants and other chemicals) observed in the marine sediment core records (Johannessen and Macdonald 2009). These contaminants show a general decreasing trend over time in many organisms including marine birds (Harris et al. 2003, 2005, Elliot et al. 2005, deBruyn et al. 2009), presumably as a result of decreases associated with discharge effluent regulation, improved treatment, remediation of contaminated sites, and other initiatives (Map 13-A).

In contrast, there appears to be an increase in polybrominated diphenylethers (PBDEs) associated with increased use over the past decade or two and an apparent increase in contaminants associated with personal care and pharmaceutical products. The production and use of PBDEs has been banned in Canada and several other countries, but they are still present in fabrics (curtains, furniture, carpeting) and electronics. These substances have been identified as having a similar combination of persistence, potential for bioaccumulation and toxicity that drew attention to the issue of PCBs (Johannessen et al. 2008a, deBruyn et al. 2009).

The increase in pharmaceutical and personal care products could be an "increase by discovery" as monitoring for these substances is a relatively new phenomenon (Johannessen et al. 2008a) and analytical methods for their detection are recent. Alternatively, they may be increasing in the environment because conventional municipal wastewater treatment systems do not remove these products. As a result, it is possible that the technological controls that have allowed population growth without substantial increase in loadings of conventional wastewater constituents such as BOD and TSS would not be adequate for removal of such products.

Six pulp and paper mills have operated on the shores of the Strait of Georgia during the period from 1990 to 2010; Squamish and Elk Falls closed in 2006 and 2010 respectively (Map 13-B). During the 1970s and 80s, these six mills were major sources of nutrients and contamination of the Strait's marine environment because they discharged large volumes of process effluents that contained pulp and bleaching chemicals including dioxins and furans (MOE 2006c). Stronger regulation and process improvement were implemented in the 1980's and have resulted in more than 100-fold reductions in loads of dioxins and furans in mill effluent. These reductions resulted in almost simultaneous reductions in levels of these compounds in crabs. Contaminant concentrations have shown a decline in sediments and accumulation in marine species monitored including crabs and birds (herons and cormorants).

10. Occurrence of non indigenous species.

Non indigenous species (NIS) are considered an environmental threat to many species and can potentially impact sockeye through introduction of species into natural ecosystems where such organisms can alter available sockeye prey or potentially interact directly with sockeye.

The Strait of Georgia and the lower Fraser River support a large number of non indigenous species (NIS), greater than twice the number found elsewhere on Canada's West Coast (Map 14). The Strait's relatively large number of NIS is a function of the long history of human development and population growth, aquaculture (e.g., shellfish and finfish), shipping (associated with transport through hull fouling and ballast water), seasonal refuge habitats, and a diversity of colonizable habitats (Map 14). The number of invasive species in the Strait has increased 40-fold since the 1880s (Gillespie 2007). It has been estimated that over 117 NIS (terrestrial and aquatic) have established populations in the Strait of Georgia and lower Fraser or along its shoreline and banks.

Gillespie (2007) estimates that as of 2007, six plant species and 29 invertebrate species had become established in intertidal habitats in the strait. In addition, another 9 fish species have been introduced into freshwater in the Lower Fraser River and an additional 2 species into the Strait of Georgia. Non indigenous smallmouth bass (*Micropterus salmoides*) and yellow perch (*Perca flavescens*) are active freshwater predators (Bradford et al. 2008a, b; Tovey et al. 2008) and have the potential to directly affect sockeye salmon survival during early life history growth in nursery habitats in Pitt, Harrison and Cultus Lakes (c.f. Ricker 1933, Schubert et al. 2002).

The largest proportion of known introductions of NIS in the Strait of Georgia and lower Fraser River has occurred in the marine inter and subtidal benthos during the past two decades. With the exception of intertidal benthos, the number of NIS in freshwater and marine environments have remained stable from 1990 to 2010.

Our Commission technical review did not include sea lice (*Lepeophtheirus salmonis*) as a NIS species because sea lice are being addressed in the Cohen Commission's aquaculture technical report.

Section 4: Human Development and Fraser Sockeye Habitat Overlap and Interactions

Section 4 is divided into two components: (a) review of results of potential interaction between human activities and sockeye habitats, and (b) issues and approaches related to fish habitat management strategies, with specific reference made to sockeye habitat.

Potential Interactions between Human Activities and Sockeye Habitats

Changes in the level of human activity in the lower Fraser River and Strait of Georgia were compared against spatial and temporal habitat use by Fraser River sockeye salmon to evaluate the potential past, current and future risk of loss or degradation to juvenile and adult Fraser sockeye salmon habitats as a result of these activities. The risk of loss or degradation of sockeye habitats is used here as a qualitative (ordinal) metric and provides one approach to classify the current and / or future change or impacts to sockeye habitats based on interaction or overlay with factors used to express changes in human activities in the lower Fraser River and Strait of Georgia. Potential interactions were reviewed over the 1990 to 2010 period across six general habitat areas (see Map 1 for delineation of these areas) within the lower Fraser River and Strait of Georgia for sockeye habitat use including:

- Lower Fraser Watersheds used as adult and juvenile sockeye for spawning and rearing habitats for month-long to year-long periods of residence;
- Lower Fraser River used as adult and juvenile sockeye migratory corridor habitat and rearing for a small proportion of 0+ juvenile sockeye for periods of days to months depending on life history stage;
- Fraser River estuary used as adult and juvenile migratory corridor and adult holding areas;
- Central Strait of Georgia used as adult and juvenile migratory corridor and adult holding areas for periods of days to weeks;
- North Strait of Georgia used as adult and juvenile migratory corridor for periods of days to weeks; and
- Juan de Fuca Strait used as adult migratory corridor and limited smolt rearing for periods of days to weeks for adults, and months for juveniles.

There are few data available to be used for quantitative evaluation and review on the amount of sockeye habitat change over time in the lower Fraser and Strait of Georgia relative to human activities. Potential impacts from human activities on sockeye habitats were reviewed by identifying the potential level of effects through a hierarchical classification and ranking method to identify substantial potential overlap with the activity and sockeye habitat and with the level of interaction.

A classification was first applied to potential interactions between human activities, identified as “factors”, and sockeye habitats generalized to six areas. A classification of “likely”, “limited” or “nil” was assigned to define the interaction. Where interactions were identified either as being “likely” or “limited”, they were further ranked to assign a level of interaction between that human activity and sockeye habitats. This ranking was based on the extent of geographic overlap, magnitude of the interaction and duration of effects used as interaction criteria between human activity and overlap with sockeye habitats (Table 1). The level of interaction between human activities and habitat areas were evaluated across an ordinal scale from nil, low, moderate or high level of interaction. A summary ranking combined predicted geographic, magnitude and duration effects to an overall level of past, current and potentially future risk of loss or degradation (interaction and overlap) of juvenile and adult (Table 2) sockeye habitats associated with human development and activities. Rankings for each of the six general habitat areas were assigned through a combination of expert opinion, the results for the factor being evaluated and an overall ranking based on the interaction criteria (Table 1). Ranks assigned to the potential for loss/degradation of sockeye habitat from human activities over the 1990 to 2010 period are detailed in Table 2, presented in Maps 15, 16 and summarized in Map 17.

Human Activities, Habitat Interactions

Table 1 presents the criteria used to first classify the interaction between human activities and sockeye habitats. Table 2 provides three sets of hierarchical results including:

i. Classification and comments of potential likely interactions or association between human activities and sockeye habitats;
ii. Assignment of potential levels of interaction among the interaction criteria (Table 1) and discussion of significance of potential interactions; and
iii. Summary ranking of level of significance of the interactions between human activities and sockeye habitat as a measure of potential risk of loss or degradation of sockeye habitats and potential links to Fraser sockeye declines.

Table 1: Human Activity Interaction Criteria Used to Classify Potential Risk of Loss or Degradation of Sockeye Habitats

Interaction Criteria	Criteria Classification	Code
Geographic Overlap Between Human Activity and Sockeye Habitats	**Nil -** No or limited spatial overlap and interaction expected between human activity and key sockeye habitats	**Nil**
	Low - There is some spatial overlap between activity and habitat used by sockeye; the activity is carried out distant from the habitat; the interaction is indirect.	**Low**
	Moderate - Moderate expected spatial overlap between human activity and habitats used by sockeye (typically edge effects); the interaction is direct but acts on small portions of a habitat.	**Mod**
	High - There is direct spatial overlap between human activity and habitats used by sockeye; the interaction is direct and acts on a high proportion of a habitat.	**High**
Magnitude of Interaction Between Human Activity and Sockeye Habitats and Habitat Use	**Nil -** The nature (physical extent, extent of activity) of the human activities is not likely to interact or induce effects on habitats used by sockeye.	**Nil**
	Low - The nature (physical extent, extent of activity) of the human activity could result in low but reversible impacts (e.g., temporary disruption of feeding) on habitats used by sockeye. Unlikely to have a population-level impact.	**Low**
	Moderate – The nature of the human activity could result in impacts that might affect some habitats used in a given run year but the impacts are reversible. The nature of the interaction is direct but does not represent a direct loss in habitat or function.	**Mod**
	High – The nature of the human activity could result in negative population and production level effects on habitats used by sockeye. The interaction results in a direct loss in habitat or function.	**High**
Duration of Overlap Between Human Activity and Sockeye Habitat Use	**Nil –** No or limited expected overlap over time between human activity extending over residence periods and use of spawning or rearing habitats, migration corridors or holding areas	**Nil**
	Low – Low expected temporal overlap between human activity and habitats used by sockeye. The interaction persists over a short duration (< 20%) of the period of use for a given habitat or can typically be mitigated through common best practice approaches.	**Low**
	Moderate – Moderate expected temporal overlap between human activity and habitats used by sockeye. The interaction persists over a moderate duration (20-50%) of the period of use for a given habitat.	**Mod**
	High – High expected temporal overlap between human activity and habitats used by sockeye. The interaction will be long duration (> 50%) or all of the period of use for a given habitats and could result in long-term effects on a habitat.	**High**

Table 2: Review of Interactions and Potential of Risk of Loss or Degradation of Fraser Sockeye Habitats Based on Interaction and Effects of Human Activities

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	Lower Fraser River	Fraser River Estuary	Central Strait of Georgia	Northern Strait of Georgia	Juan de Fuca Strait
1. Population (Population Size)						
Likely Interaction	○	●	●	○	Nil	Nil
Interactions with Sockeye Habitats	• Much of the population growth and urbanization (population density) has occurred along the lower Fraser River and Fraser Estuary (Map 5). • In the Strait of Georgia and Juan de Fuca Strait the interaction of population centres with sockeye habitat is not significant because of the extent and type of marine habitat used (Section 2). • Limited population growth and urban and industrial development has occurred or changed over the past two decades around upper sockeye watersheds in the Harrison, Pitt and Chilliwack.					
Geographic Overlap	Low	Mod	Mod	Nil	Nil	Nil
Magnitude of Interaction	Low	Low	Low	Low	Nil	Nil
Duration of Interaction	Low	Low	Low	Nil	Nil	Nil
Significance of potential interactions	• While there is moderate geographic overlap as a result of potential edge effects, the magnitude of interaction with sockeye habitat is considered to be low given the effective application of environmental mitigation practices and habitat compensation during project review, design and construction (Section 4). • Although the duration of interaction is high, it has been ranked as low because it is expected that habitat conservation strategies will avoid and limit negative interactions with sockeye habitat.					
Summary Risk of Loss or Degradation of Sockeye Habitats	Low	Low	Low	Nil	Nil	Nil
Potential links to Fraser sockeye declines	• Overall, the risk of development on sockeye habitat is ranked as low because there is evidence of a net habitat gain rather than loss. This has not been ranked as Nil in the Fraser watersheds, lower Fraser River and estuary because there are certain indirect effects that are related with population growth. • In the lower Fraser River and Harrison, Pitt, Chilliwack watersheds, the proximity of growth to key sockeye habitats is relatively localized in relation to the overall distribution of sockeye habitats, with the possible exception of the Cultus Lake stock in the Chilliwack watershed. • The ranking assumes that into the future, an effective habitat management system will remain in place. • Factors directly linked to population growth do not have a clear or apparent causal link to the Fraser sockeye decline.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	Lower Fraser River	Fraser River Estuary	Central Strait of Georgia	Northern Strait of Georgia	Juan de Fuca Strait
2. Land use (Agriculture / Forestry)						
Likely Interaction	●	○	○	○	Nil	Nil
Interactions with Sockeye Habitats	• An interaction between agricultural and forestry land use and sockeye habitats is likely in the lower Fraser watersheds but limited in the lower Fraser and estuary (Map 6, 7). • Agricultural and forestry activities in the Strait of Georgia and Juan de Fuca Strait do not interact with the key sockeye habitats. There is little or no evidence to suggest that indirect effects (runoff quality) from these land uses are negatively impacting water quality and sockeye habitats.					
Geographic Overlap	Mod	Low	Low	Nil	Nil	Nil
Magnitude of Interaction	Mod	Nil	Nil	Nil	Nil	Nil
Duration of Interaction	High	Nil	Nil	Nil	Nil	Nil
Significance of potential interactions	• Agricultural land use and activities in some of the lower Fraser watersheds have intensified and expanded. • Diking for agricultural purposes is not active in recent years, dredging of river substrates to protect against flooding will result in disruptions to sockeye habitats, particularly in the Chilliwack/Cultus areas (Map 11). Diking activities have limited duration, the timing of which does not overlap with sockeye habitat use. • There are risks of water quality impacts due to over application of manure, fertilizer application and other activities, erosion and runoff in the lower Fraser watersheds. • Incubation and spawning habitats are in proximity to forest lands, resulting in a rating of high for duration; however, duration is brief adjacent to agricultural lands because of rapid outmigration of sockeye in areas near agriculture activity.					
Summary Risk of Loss or Degradation of Sockeye Habitats	Mod	Nil	Nil	Nil	Nil	Nil
Potential links to Fraser sockeye declines	• The Cultus Lake sockeye stock in the Chilliwack watershed would have the most likely exposure to agriculture, resulting in a rating of moderate for the Fraser watersheds. • There is limited or indirect influence on Strait of Georgia and lower Fraser and Fraser estuary. • Improved practices have reduced effects of forestry and to some extent agriculture. • An overall rating of moderate has been assigned to the Fraser Watersheds area because land use stressors could be having an effect, although data for managed/natural spawning habitats does not suggest that incubation quality is impaired (forestry) and because duration of exposure in agricultural areas is considered brief during adult and juvenile migration. • Association to 1990-2009 declines is not likely.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	Lower Fraser River	Fraser River Estuary	Central Strait of Georgia	Northern Strait of Georgia	Juan de Fuca Strait
3. Large Industrial and Infrastructure Projects						
Likely Interction	Nil	●	●	○	○	Nil
Interactions with Sockeye Habitats	• The development of large infrastructure projects is largely concentrated in the lower mainland of BC (Map 8).					
Geographic Overlap	Nil	Mod	Mod	Nil	Nil	Nil
Magnitude of Interaction	Nil	Low	Low	Low	Low	Nil
Duration of Interaction	Nil	Low	Low	Nil	Nil	Nil
Significance of potential interactions	• The projects are located on the edge of key sockeye habitats in the lower Fraser River and its estuary. • The magnitude is rated as low because construction-related impacts can be mitigated and the habitat gains are required for reviewed projects which cause habitat loss. • Duration is low in the lower Fraser River because residence period is limited for most sockeye using the river as a migration corridor.					
Summary Risk of Loss or Degradation of Sockeye Habitats	Nil	Low	Low	Nil	Nil	Nil
Potential links to Fraser sockeye declines	• Overall ranking for major project development is Nil for several habitat areas because of limited project development work adjacent to sockeye habitat. • A Low ranking was assigned for areas adjacent to sockeye habitat in the Lower Fraser area because the evidence available indicates that habitats have not been in a state of decline over the 1990 - 2010 period.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	Lower Fraser River	Fraser River Estuary	Central Strait of Georgia	Northern Strait of Georgia	Juan de Fuca Strait
4. Waste (Liquid / Solid)						
Likely Interaction	○	●	●	Nil	Nil	Nil
Interactions with Sockeye Habitats	• There are several wastewater treatment plants in the lower Fraser area associated with large urban centres (Map 9). • Wastewater discharges also occur in the Strait of Georgia/Juan de Fuca Strait; however, interaction with sockeye habitat is not expected to be significant. • Solid waste is disposed in landfills with little or no spatial overlap with sockeye habitats.					
Geographic Overlap	Nil	High	High	Nil	Nil	Nil
Magnitude of Interaction	Low	Low	Low	Nil	Nil	Nil
Duration of Interaction	Nil	Low	Low	Nil	Nil	Nil
Significance of potential interactions	• There is a high overlap with wastewater effluents and sockeye habitats in the lower Fraser River and estuary because the effluents discharge through submerged outfalls and the dilution zone would occur in a substantial part of the Fraser River and estuary. • Landfilling in the lower mainland has been decreasing over the period of study. New landfills are constructed (old ones retrofitted) with leachate control to limit ground or surface water contamination. • The magnitude of effects from wastewater treatment discharge (nutrients, total suspended solids) has been decreasing over the period of time under study as treatment plants have been expanded and upgraded to become more effective (e.g., Annacis Island). • Personal care and pharmaceutical products show an apparent increase in the environment; however, this may be due to an increase in monitoring efforts/methods to identify these products rather than reflecting an increase in use.					
Summary Risk of Loss or Degradation of Sockeye Habitats	Nil	Low	Low	Nil	Nil	Nil
Potential links to Fraser sockeye declines	• Solid and liquid waste disposal management and practices have improved over the past two decades. • Limited or local influence on Strait of Georgia; existing sewage receives high dilution and duration of overlap with sockeye would be low. • An overall rating of Low has been assigned for the lower Fraser River because there is some overlap with habitat used but the duration of overlap would be low. • During the period of decline, significant upgrades to sewage infrastructure have occurred.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	**Lower Fraser River**	**Fraser River Estuary**	**Central Strait of Georgia**	**Northern Strait of Georgia**	**Juan de Fuca Strait**
5. Shipping and Vessel Traffic						
Likely Interaction	n/a	n/a	○	○	○	○
Interactions with Sockeye Habitats	• Shipping and vessel traffic routes have a high degree of overlap with the areas used by sockeye; however, direct interaction is not likely (Map 10). • Infrastructure associated with shipping/vessel traffic (e.g., port facilities) is evaluated separately in the table for large industrial and infrastructure projects).					
Geographic Overlap	n/a	n/a	Mod	Mod	Mod	Mod
Magnitude of Interaction	n/a	n/a	Low	Low	Low	Low
Duration of Interaction	n/a	n/a	Nil	Nil	Nil	Nil
Significance of potential interactions	• Interaction of vessels moving through water with sockeye is expected to be limited because habitat use does not directly overlap and because vessels are likely to displace fish, if encountered. The duration of encounter would be limited. • Ballast water discharge and potential invasive species introduction have been limited in recent years. This topic is examined in factor #10 below. • Regulations and options (on-board treatment, disposal) for shipboard sewage and ballast discharge disposal have been improving. Sewage from pleasure craft unlikely to directly impact on sockeye. • Marina and shipyard practices are improving and facilities for sewage pump out are increasing.					
Summary Risk of Loss or Degradation of Sockeye Habitats	n/a	n/a	Nil	Nil	Nil	Nil
Potential links to Fraser sockeye declines	• Although there is an overlap with some of the areas used by sockeye and by vessel navigation, the duration is low and mechanisms of direct interaction are limited. • Shipping, boating and marina practices have been improving over the period of study. • The evidence does not indicate that ship vessel traffic has been increasing over the period of study. • Patterns of vessel movement, nature of operation (discharges) have been improving and are thus unlikely to be related to the decline in Fraser sockeye production.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	Lower Fraser River	Fraser River Estuary	Central Strait of Georgia	Northern Strait of Georgia	Juan de Fuca Strait
6. Dredging, Diking, Disposal at Sea						
Likely Interaction	●	●	●	○	n/a	n/a
Interactions with Sockeye Habitats	• Diking and dredging will likely interact with sockeye habitats in the lower Fraser River and estuary and in portions of the Fraser Watersheds (Map 11).					
Geographic Overlap	Low	Low	Low	Low	n/a	n/a
Magnitude of Interaction	Low	Low	Low	Nil	n/a	n/a
Duration of Interaction	Nil	Low	Low	Nil	n/a	n/a
Significance of potential interactions	• The original dike construction was undertaken prior to the 1950's and before the period of study; however, some impacts remain related to the loss of off-channel areas, and the confinement of main channel flow. • Some dikes have been removed or opened to restore fish habitats and provide access to off channel areas. • Dredging in the Fraser River does not directly overlap with migratory habitats used by sockeye (depth differences); however, there may be some flood-control related dredging in the Fraser watersheds that could have temporary disruptions on those habitats but they would occur outside of the period of direct habitat use. • Disposal at sea does not directly interact with sockeye habitats.					
Summary Risk of Loss or Degradation of Sockeye Habitats	n/a	Low	Low	Nil	n/a	n/a
Potential links to Fraser sockeye declines	• Diking in the lower Fraser River and estuary occurred prior to 1950's (outside of the time period under study) and thus dike construction was not a factor in the summary rankings. • Habitat restoration initiatives have added habitat in areas previously blocked behind dikes (see *Inset 1, 2, 3* for some examples). • Dredging activities and dredged sand volumes have declined annually for the past two decades. • Changes in these activities do not coincide with declines in the Fraser sockeye. • Diking is likely to have ongoing impacts on the Fraser River channel characteristics.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	**Lower Fraser River**	**Fraser River Estuary**	**Central Strait of Georgia**	**Northern Strait of Georgia**	**Juan de Fuca Strait**
7. Strait of Georgia Water Properties						
Likely Interaction	n/a	n/a	●	●	●	●
Interactions with Sockeye Habitats	• There is direct interaction with marine conditions and characteristics in the Strait of Georgia for all general habitat areas except lower Fraser watershed and river (Map 12).					
Geographic Overlap	n/a	n/a	High	High	High	Mod
Magnitude of Interaction	n/a	n/a	Nil	Mod	Mod	Nil
Duration of Interaction	n/a	n/a	Low	Mod	Mod	Nil
Significance of potential interactions	• There is direct and spatially large geographic overlap with habitats used by sockeye. • Reduced incremental rearing productivity (growth and survival) in Strait of Georgia habitats may be occurring, and could be resulting in large scale changes across broad areas of sockeye habitat use. • Associated changes in sockeye food availability, competitors and predators may occur with variation and changes in seasonal and annual conditions (temperature, salinity, Fraser River discharge, winds acting on sea surface, currents). • Effects of warming observed in the Strait of Georgia. Juan de Fuca Strait influenced by Pacific Ocean water movement.					
Summary Risk of Loss or Degradation of Sockeye Habitats	n/a	n/a	Low	Mod	Mod	Nil
Potential links to Fraser sockeye declines	• These are large-scale changes over the extent of the Strait of Georgia that have the potential for population-level effects through impacts on ecosystem structure including food availability/quality, competitor and predator abundance. Moderate and low rankings in this table reflect that the water properties are not acting directly on the sockeye but rather on their prey (see table below) • Sockeye production (growth and survival) is expected to be higher when sockeye growth and condition prior to moving offshore are high, relative to poorer sockeye production in years, seasons and habitats linked to lower growth and condition. Cooler years in the Strait of Georgia are expected to have higher abundance and availability of preferred (larger sized, higher energy content) sockeye prey and lower levels of competitors and predators.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	Lower Fraser River	Fraser River Estuary	Central Strait of Georgia	Northern Strait of Georgia	Juan de Fuca Strait
8. Strait of Georgia Biological Properties						
Likely Interaction	n/a	n/a	●	●	●	●
Interactions with Sockeye Habitats	• There is direct and spatially large geographic overlap with habitats used by sockeye (Map 12). • Reduced incremental rearing productivity in Strait of Georgia habitats may be occurring, resulting in large scale changes across broad areas of sockeye habitat use. • Associated changes in ecosystem structure and function for sockeye preferred food availability, competitors and predators may occur with variation and changes in seasonal and annual conditions.					
Geographic Overlap	n/a	n/a	Low	High	High	Low
Magnitude of Interaction	n/a	n/a	Low	High	High	Nil
Duration of Interaction	n/a	n/a	Nil	Mod	Mod	Nil
Significance of potential interactions	• Reduced incremental rearing productivity (growth and survival) Strait of Georgia habitats. • Sockeye production is expected to be higher when sockeye growth and condition are high, relative to production in years, seasons and habitats linked to lower growth and condition. Cooler years in the Strait of Georgia are expected to have higher abundance and availability of preferred (larger sized, higher energy content) sockeye prey and less competitors/ predators relative to warmer years. • Effects of warming observed in the Strait of Georgia. Juan de Fuca Strait influenced by Pacific Ocean water movement.					
Summary Risk of Loss or Degradation of Sockeye Habitats	n/a	n/a	Nil	High	High	Nil
Potential links to Fraser sockeye declines	• Reduced incremental rearing productivity in Strait of Georgia habitats related to recent trends in warmer years (Map 12-A). • Warmer years infer reduced growth and condition of sockeye and enhanced vulnerability to predation • Changes observed to types of available food prey, reduced availability of cool water plankton prey (e.g., *Neocalanus sp.*). • Enhanced competition with warm water species for available food and increased stress in warmer water conditions during spawning migrations. • Changes in water and biological conditions appear to be temporally and mechanistically linked to declining sockeye production (ranked as high) but conclusive causal linkage cannot be made.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	Lower Fraser River	Fraser River Estuary	Central Strait of Georgia	Northern Strait of Georgia	Juan de Fuca Strait
9. Contaminated Materials						
Likely Interaction	Nil	○	○	○	○	Nil
Interactions with Sockeye Habitats	• Distribution of contaminants associated with areas of long term effluent discharge associated with pulp and paper mills and wastewater treatment plants (Map 13). • Limited discharge and known contamination in the freshwater watersheds adjacent to sockeye habitats • Large dilution of discharge in Strait of Georgia and Juan de Fuca Strait.					
Geographic Overlap	Nil	Mod	Mod	Low	Low	Nil
Magnitude of Interaction	Nil	Low	Low	Nil	Nil	Nil
Duration of Interaction	Nil	Low	Low	Nil	Nil	Nil
Significance of potential interactions	• Low to moderate geographic overlap with sockeye habitats in coastal areas. • Limited magnitude of interaction due to dilution. • Low level of overlap in migration habitats for juvenile and adult sockeye					
Summary Risk of Loss or Degradation of Sockeye Habitats	Nil	Low	Low	Nil	Nil	Nil
Potential links to Fraser sockeye declines	• No or low ranking related to effects on sockeye production. • Contaminants can potentially exacerbate stress related to warmer environmental conditions experienced by migrating salmon, particularly for migrating adult returning to spawn. • In areas of sockeye production, contaminant levels are low and exposure duration is brief.					

Human Activities	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	**Lower Fraser River**	**Fraser River Estuary**	**Central Strait of Georgia**	**Northern Strait of Georgia**	**Juan de Fuca Strait**
10. Non Indigenous Species Introductions						
Likely Interaction	○	○	○	○	Nil	Nil
Interactions with Sockeye Habitats	• Enhanced introduction of non indigenous species through human development and activities including shipping, aquaculture and recreation (Map 14). • Introduction into freshwater and marine environments primarily associated with fish and benthic invertebrate introductions; however, invasive plants (purple loosestrife) will also interact with sockeye habitats (Fraser River marsh).					
Geographic Overlap	Low	Low	Low	Nil	Nil	Nil
Magnitude of Interaction	Low	Low	Low	Low	Nil	Nil
Duration of Interaction	Mod	Low	Low	Low	Nil	Nil
Significance of potential interactions	• NIS that would interact with sockeye are, at this time, not widely distributed. • Several of the NIS are located in habitats not widely used by sockeye (e.g., benthic habitat in Strait of Georgia).					
Summary Risk of Loss or Degradation of Sockeye Habitats	Low	Low	Low	Nil	Nil	Nil
Potential links to Fraser sockeye declines	• The number of non indigenous species in freshwater and marine environments which coincide with sockeye use are limited and have remained stable over the study period.					

Habitat Protection Strategies

As part of our review, we examined lower Fraser River and Fraser estuary development activities and the habitat protection and conservation strategies, primarily within the lower Fraser River and estuary and more generally within the Strait of Georgia. This review is based on the information referred to in this report and the authors' habitat management and project experience in the lower Mainland and Strait of Georgia area. This habitat experience includes habitat science, biological monitoring, enforcement and participation in the project assessment and review process from the perspective of government and consultants employed by clients in industry and government.

Sockeye Habitat Conservation Strategies

Canada's primary legislative tool for fish habitat conservation and protection[2], including sockeye salmon habitats, is the Canada *Fisheries Act*. The Act provides an effective backbone for a habitat protection strategy; the modern form of the Act is biological in nature and implicitly acknowledges the need to protect the physical habitat (administered by DFO) for all life stages of sockeye, including their food source and it protects the quality of the water in which they live (administered by Environment Canada). The habitat protection provisions in the Act have been in place since 1976/1977. Prior to then, habitat destruction was not prohibited and considerable habitats in the Fraser River estuary were irreversibly lost, for instance through diking and loss of marsh channels and other marsh habitats (see Map 11-B, for example, Levings 1998, Ham and Church 2002, Ellis et al. 2004). Subsequent to the habitat provisions coming into force, the manner in which DFO administers the Act and brings about conservation of fish habitats is implemented under DFO's habitat policy (DFO, 1986). The policy seeks to achieve a "net gain" in fish habitat and, in the lower Fraser River, relies primarily on implementation of the first two policy goals to accomplish this including:

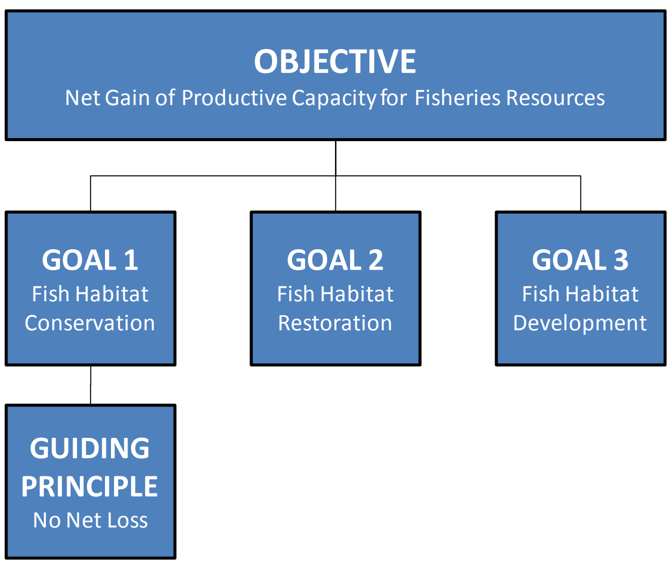

Figure 7. Habitat Policy Management Framework used in the Lower Fraser River and Strait of Georgia

[2] The terms "protection" and "conservation" are often used interchangeably; however, the difference in meaning is substantial when considered in the context of habitat management. Protection means that if an area is habitat, no change whatsoever is permitted. Conservation means that a loss of that habitat is not acceptable but alterations to it, if offset, will be considered. These terms have very direct implications for development and habitat management.

- Fish habitat conservation – this policy goal adopts a “no net loss” guiding principle and this aspect of the habitat policy is most frequently encountered as part of the review of development projects that may affect Fraser River sockeye habitat.
- Resource Restoration – this goal seeks to restore previously lost or damaged habitats (*e.g.*, off-channel habitats lost due to historical diking activity). DFO’s Salmonid Enhancement Program has an active leadership role in habitat restoration, this activity is most commonly carried out in partnership with provincial and local governments and non-government organizations and community stewardship groups.

The habitat policy has a conservation focus; alterations to fish habitat are, if demonstrated to be necessary and unavoidable, permitted through the granting of a *Fisheries Act* Authorization and one is only granted if the habitat alteration/loss is offset by a habitat gain (habitat compensation). An example of the no net loss principle with relevance to sockeye habitat is described below in *Inset 1*. The habitat policy, together with the Act, forms the basis for fish habitat conservation in Canada.

Within the lower Fraser River, downstream of the mouth of Kanaka Creek, all projects on the river side of the top of bank are reviewed by the Fraser River Estuary Management Program (FREMP) Environmental Review Committee (ERC). This review process was set up with the objective of offering a one-stop review process for proponents and the process brings together the authority and the influence of major partners in the estuary (and Burrard Inlet) including federal and provincial agency representatives. At a planning stage, FREMP also include local and regional governments that operate adjacent to the lower Fraser River. The coordinated project review processes have functioned over the years to modify the design of projects, identify opportunities to mitigate harmful effects or develop habitat compensation for projects that might otherwise result in a loss of fish habitat quantity or quality.

More recently, major projects have been reviewed outside of the FREMP ERC forum through processes that are managed through a harmonized federal/provincial environmental assessment process under appropriate federal and provincial environmental assessment acts. Components of this environmental assessment and review may be broader in scope than those reviewed in the ERC but will include similar factors to assessment and review potential effects on sockeye habitats. In areas outside of FREMP, the nature of cooperative arrangements and how the DFO policy/Act becomes invoked within the process of shoreline and instream development activities is more variable; however, the guiding principle of no net loss of aquatic habitat is pursued in a similar manner and is often the primary trigger for review under the *Canadian Environmental Assessment Act*.

Development Activity and Impacts on Sockeye Habitat

An objective of this report is to examine whether or not the development of major projects (industrial and infrastructure) impact sockeye habitats and whether potential habitat impacts can be linked to declines in Fraser River sockeye salmon (see Map 8).

There are few data available for a quantitative analysis of the amount of fish habitat change over time in the lower Fraser and Strait of Georgia. However, the goal of this component of our review is more narrowly focused on identifying whether or not major project development has led to decreased sockeye salmon production through changes in habitats over the period of 1990 to 2010.

To examine whether or not habitat loss/degradation from major project development might be a factor in the 1990 to 2009 Fraser River sockeye salmon declines, we compiled available information on sockeye habitat use (described in Section 2 and Appendix 3, Maps 3 – 4) that might be impacted by development of projects within the lower Fraser River and estuary to evaluate if sockeye habitats are declining concurrently with declining sockeye stocks. If the sockeye habitats are declining as a result of project development in the lower river and estuary concurrent with the

INSET 1:
Pitt River Intertidal Wetland, Port Coquitlam, BC: An Application of the "No Net Loss" Principle

Photo 1. A recent habitat compensation project near the Pitt River/Fraser River confluence at Port Coquitlam. *Photo courtesy of Conwest Contracting Ltd. taken by Waite Air Photography*

The Pitt River Intertidal Wetland at the confluence of the Pitt River and Fraser River, is a habitat compensation project constructed by the City of Port Coquitlam, in partnership with private developers. The authorized habitat loss comprised infilling of road side ditches and an open drainage system emptying to the Pitt River through pump stations. The offset to this habitat loss was the gain of 6.5 hectares of wetland and riparian forest. The Fraser dike was relocated inland (the raised road system in the photo), creating off-channel salmon habitat no longer associated with the drainage system. The project has created a large habitat complex of an ecological value that is considered greater than that of the habitats lost. Sockeye salmon juveniles (river type), as well as other fish species, are expected to use this habitat complex.

sockeye production declines, this observation would suggest that project development in these areas may be a factor in the declines of sockeye. Conversely, if the information suggests that habitats are not declining (taking into account the lag time between habitat loss, sockeye life history and impact on sockeye salmon population estimates), this information would suggest that habitat impacts of project development in the lower river and estuary are an unlikely cause or major factor associated with 1990-2009 Fraser River sockeye salmon declines. As noted previously, the present review is focused on Fraser River sockeye habitat. This review should therefore not be looked upon as an evaluation of the habitat status for other fish species' habitats and habitat use in lower Fraser River and Fraser estuary.

Harper and Quigley (2005) reviewed project-related habitat losses and gains from 105 projects located in British Columbia (83 in the Fraser River) and found that there was a net gain of 24,064 m^2 of estuarine habitat and 10,900 m^2 of marine habitat. The data provided by Harper and Quigley (2005) did not provide details on where the projects and habitats reviewed were located or whether or not they included sockeye habitats. However, these results suggest that at least for individual projects, the habitat protection strategies are, on balance attaining the objective of conserving and in part supporting habitat gains as part of a project's environmental review. Opportunities to enhance currently degraded habitats often depend on the confluence of a development/infrastructure project to fund the habitat restoration and a regulatory driver (*e.g., Fisheries Act*) to compel habitat conservation and compensate for habitat losses as the project is planned, reviewed, constructed and operated throughout its own life cycle.

The view regarding a net gain does have a notable uncertainty in the ability to extrapolate from these data across the whole of the lower Fraser River because the data are collected for each individual project under environmental review by DFO. The data do not provide a broad overview or summary of the amount of habitat gained/lost outside of the framework of a project review process and do not include losses from unlawful activities.

Not all habitat compensation projects have worked as intended. Kistritz (1996) and Adams and Williams (2004) documented the outcome of a number of habitat compensation projects that have been undertaken in the Fraser River Estuary. Not surprisingly, they found that earlier efforts at marsh creation were not consistently effective to balance habitat losses, in part because of poor quality control over site preparation, vegetation planting and inadequate design criteria and standards. Kistritz (1996) and Adams and Williams (2004) provide detailed examples of these earlier efforts.

Kistritz (1996) reviewed project files for the period of 1983 – 1993 for habitat gains and losses and the extent to which the no net loss policy was achieving its goals. Most of the files reviewed by Kistritz (1996) precede the timeframe of the present review; however, the report does provide quantitative insight into some of the earlier habitat projects. Over the period of his review (1983-

1993), Kistritz (1996) found that habitat loss occurred, particularly for subtidal and mud/sandflat habitats, although there were net gains as a result of restoration projects and marsh construction projects. The losses noted in the Kistritz (1996) report were largely attributed to losses associated with specific projects occurring on Roberts Bank. While these losses occurred outside of the present study period, habitat losses could have a lag time resulting in loss of salmon production. With specific reference to sockeye, Map 3-B-ii shows no or low sockeye habitat use at this sites (Barraclough and Phillips 1978, Levings, 1985; Greer et al., 1980); while other species of salmon were found to use those areas, the habitat losses noted by Kistritz (1996) would not have significant implications for Fraser sockeye.

The implications of unsuccessful habitat compensation projects in the Fraser River estuary can be significant (e.g., Levings and Macdonald 1991, Levings and Nishimura 1997), particularly with regard to cumulative losses of rearing habitat for river type sockeye as well as for other species of fish. The knowledge that is needed to plan and construct effective artificial habitats is an important component to fish habitat conservation. In the absence of such knowledge, the strength of the conservation-oriented elements of the fish habitat policy could be diluted because those elements are reliant on the functional success of constructed habitats.

The need to monitor and manage the construction of compensatory habitat, its effectiveness and to manage unsuccessful habitat compensation projects has been addressed, at least to a degree, through the regulatory process under which habitat is managed (i.e., the Act and policy implementation). Monitoring programs for compensatory fish habitat are now standard requirements contained within the environmental application and regulatory authorization to construct and operate a project. As documented by Adams and Williams (2004) and Wilson et al. (2002) and as is no doubt evident to many habitat managers and scientists, the collection and capture of systematic data on the factors that determine habitat restoration project effectiveness and success could be improved. However, there is evidence to suggest that research carried out on past habitat projects has resulted in better habitat compensation design as more recent projects tend to be successful (Adams and Williams, 2004; Wilson et al., 2002; Levings and Nishimura, 1997). The collection of data from the various types of habitats that have been constructed either as a result of compensation requirements or habitat that has been constructed as part of a habitat restoration project would provide, for example, valuable insight into factors that need to be incorporated into future habitat design specifications, the rates of colonization of newly constructed habitat and the actual usage by fish and other species (Hartman and Miles 1995, Wilson et al. 2002). The importance of habitat science will be a necessary component of fish habitat conservation as population and economic pressures challenge existing space and current methods for habitat compensation (e.g., construction of marshes).

In its present form, the value of habitat monitoring is seldom realized without extensive project-by-project review (see for example Adams and Williams, 2006; Kistritz 1996; Hartman and Miles 1995; Quigley and Harper 2005) and even then, is limited by the availability of quantitative data and the presence of compatible biological variables and study methodology between monitoring programs. In this respect, the lack of coordination along the continuum of designs, monitoring and data management represent a potentially foregone opportunity for scientific return on both public and private (e.g., project proponent) expenditures through this continuum. The cost of constructing and monitoring is not insignificant and a coordinated process to capture data would provide a better knowledge base from which to manage fish habitat into the future. Reliable local monitoring data on the success factors for habitat restoration design and future ecological function will aid in the development and evaluation of habitat compensation proposals.

Habitat Restoration

Considerable amounts of fish habitat have historically been lost from the lower Fraser River and estuary through a variety of human activities that were carried out before the physical components of fish habitat were protected in *Fisheries Act* (i.e., pre-1976). Extensive diking was initiated in the early 1900's in response to flooding and the scale of changes from diking has resulted in a large reduction in floodplain and active channel size over the last century (Ham and Church, 2002; see also Map 11-B). Construction of dikes has been linked to loss of secondary and off-channel salmon

Photo 2. Addington Point Marsh habitat restoration project. *Photo courtesy of Dan Buffett, Ducks Unlimited.*

INSET 2:
Example of a Habitat Restoration Project

The Addington Point Marsh was diked a century ago for use as a livestock pasture, cutting off access and use by fish. In 2004, partnership of government (DFO, Ministry of Environment) and non-government organizations (Ducks Unlimited, BC Habitat Conservation Trust Fund and the Nature Trust of BC) opened access from the Pitt River to this 260 ha marsh by breaching dikes to allow a tidal floodplain ecosystem to develop and allow the passage of fish between the off-channel marsh and the Pitt River. The Pitt River, part of the Fraser River system, has sockeye salmon spawning populations in the Widgeon Creek and upper Pitt River areas.

habitats, including those habitats potentially used by 0+ river-type sockeye. The watercourses and off-channel habitats were cut off from the Fraser River by dikes and pump drained systems which present a barrier to fish movement. These changes pre-date the study period reviewed in this report (1990-2010) and potential impacts on sockeye habitat loss and possible sockeye production decreases are likely to have been realized prior to the period of present study.

Diking activities in the early part of the century (Map 11-B; Appendix 3) have an associated historic habitat loss estimated to be at least 40% of pre-impact habitats (Ellis et al. 2004) and this understanding has led to efforts to reverse some of those habitat losses. *Inset 2* provides an example of a large restoration project along the Pitt River that in 2004 reversed losses due to diking by breaching the dikes and allowing free passage of fish into a 260 ha marsh. In the last 3 to 4 decades, habitat restoration activities have led to gains in sockeye-accessible habitat in the lower Fraser River and estuary. In some cases, these gains have been realized as the result of opportunities arising from development projects (see *Inset 1* for example) and in other cases, they have been realized as the result of a purely restorative effort (see *Inset 2, 3*). Habitat conservation through resource restoration has a broad base of support as the significant restoration projects are

INSET 3:
Burnaby Big Bend Habitat Restoration Project, Burnaby, BC

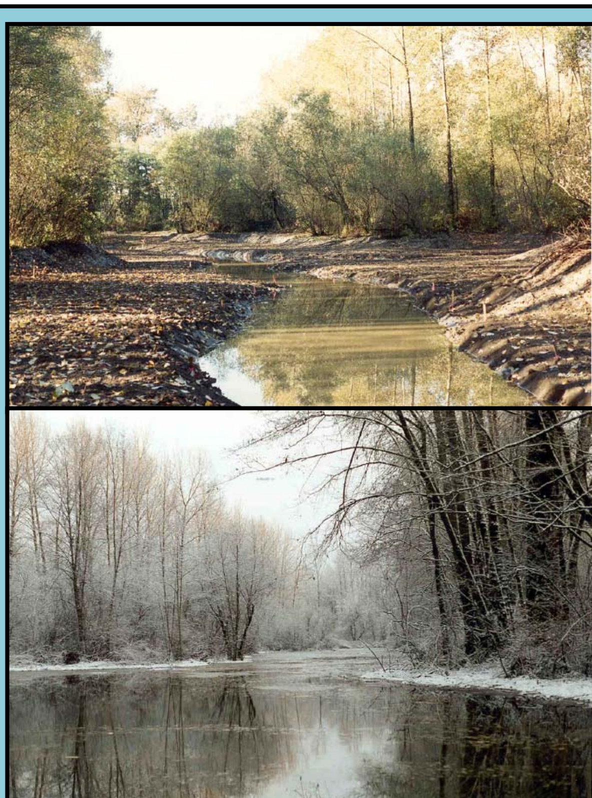

Photo 3. Burnaby Big Bend tidal channel under construction at low tide (top) and after construction at high tide (bottom). *Photo courtesy of Matt Foy, DFO*

Much of the Fraser River estuary marsh and slough habitat has been lost as a result of historical diking and other development-related activities. Such areas provide important feeding habitats for various fish species, including sockeye. The Big Bend area of Burnaby, adjacent to the Fraser River North Arm is a forested area of land behind degraded dikes. The area presented an opportunity to restore habitat of a type that had become rare in the North Arm. The Big Bend habitat project (> 18,000 m^2 of habitat gain) is a complex of intertidal slough and marsh habitat, constructed through a partnership of DFO and the City of Burnaby. The ecological success of this project was evidenced through fish sampling that found juvenile river-type sockeye rearing in this constructed habitat.

almost exclusively carried out through partnerships between resource management agencies such as DFO (Salmonid Enhancement Program, Resource Restoration) and the BC Ministry of Environment, various non-government organizations and local/regional governments.

A summary of select habitat restoration projects carried out under the guidance of DFO's Salmonid Enhancement Project is provided in Table 3. These restoration projects were selected from DFO's habitat restoration projects because they are expected to provide benefits to Fraser River sockeye salmon and because, to date, these projects continue to provide habitat functions as originally planned and constructed. Within these habitat restoration projects, spawning sockeye salmon have been confirmed by DFO in the Upper Pitt River, Alvin Patterson Channel and in Big Silver side channel projects. Rearing sockeye salmon juveniles have also been confirmed in the Big Bend Channel project (*Inset 3*). In total, 2.7 million m^2 of habitat gains (i.e., "net gain") have been realized through resource restoration efforts.

Table 3. A summary of restoration projects and estimated areas salmon habitats created.

Watershed	Restoration Project Name	Year	Estimated Area (m^2)
Lower Fraser River	Ladner Lagoon Slough	1988	4,800
Lower Fraser River	MacDonald Slough	1990	13,750
Big Silver Creek	Big Silver Side Channel	1992	45,000
Lower Fraser River	Big Bend Channel (*Inset 3*)	1994	18,740
Lower Fraser River	Annacis Island Channel	1995	4,800
Upper Pitt River	Alvin Patterson Channel	1997	8,700
Lower Fraser River	Douglas Island Channel	2001	1,300
Coquitlam River	Colony Farm 1	2004	3,800
Pitt River	Addington Point Marsh (*Inset 2*)	2004	2,600,000
Coquitlam River	Colony Farm 2	2008	3,750
		Total	**2,704,640**

Data provided by Matt Foy, Salmonid Enhancement Program, Lower Fraser Area Office, Resource Restoration (DFO)

Human Activities, Habitat Interactions and Sockeye Production

Data on habitat gains and losses comes available largely as a result of the occasional review of habitat authorization files held by DFO and/or FREMP. These data are therefore skewed to the representation of data on habitat gains and losses as encountered during the regulatory project review process. A comprehensive inventory of sockeye habitat, independent of data maintained as the result of project review, is not available and thus the status of total sockeye habitat gains and losses in the lower Fraser River and Strait of Georgia cannot be quantified. However, with respect to project development and activities and habitat restoration in the lower Fraser River and estuary the following observations are pertinent:

- A legal and policy framework is in place to facilitate the conservation of sockeye habitat;

- The implementation of that framework in regards to development projects in the lower Fraser River and estuary has resulted in a net gain of fish habitat because of favourable habitat compensation gain versus losses applied by existing policy;
- There is evidence to suggest that both the quantity and quality of sockeye habitat, at least in relation to development projects under environmental assessment and review, has improved over the past two decades.

Habitat restoration has resulted in a reversal of some of the kinds of losses that occurred during the earlier part of the past century. In a contemporary context (i.e., not including losses antecedent to the period of study), these restoration efforts amount to a gain in sockeye habitat in the lower Fraser River (Table 3).

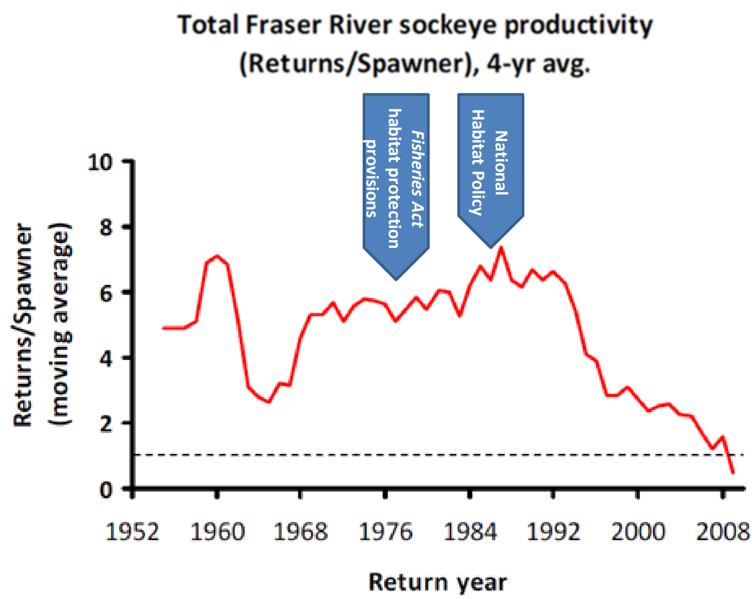

Figure 8: Fraser River Sockeye Productivity Index using a four-year moving average over the Period 1950s – 2009 compared against implementation of key sockeye habitat protection mechanisms. The dashed line shows the ration of recruits to spawner replacement (=1). Source: Grant et al. 2010, M. Lapointe, PSC 2010, in Peterman et al. 2010.

Overall, the development of major projects and resource restoration efforts during the period 1990 – 2010 has resulted in an apparent net gain of sockeye habitat. Throughout the period (pre-1976) when fish habitat did not receive protection under the *Fisheries Act*, the Fraser River sockeye salmon returns do not appear to have been in a state of decline (Figure 8). The decline occurred only after the habitats had received protection. Quantitative habitat data do not exist that would permit a statistical review of the potential association between sockeye number and sockeye habitat area. There is evidence that habitat losses from projects that have undergone environmental review over the period of this study have not occurred and may even suggest that habitat protection/conservation strategies have been effective for those habitats which are used by Fraser sockeye. More broadly, a hypothesis that the declines in the Fraser River sockeye adult returns (Figure 8) are the result of the development of major projects is not supported by the likely net gains in habitat that have occurred during the review of major projects following implementation of the “no net loss” policy.

The habitat protection strategies employed appear to be effective at the major project review and project-related activities (e.g., construction of a specific project). Implementation of the habitat policy to management of non-point source impacts on habitats is more difficult to evaluate because effects are often diffuse and data capture for such effects does not allow an analysis of those impacts. Such an evaluation would require more frequent monitoring, along with data collection across spatially broad areas associated with residential development and a variety of land uses (agriculture, forestry). Activities such as logging or urban / industrial development are known to have the potential to result in watershed level changes that could result in the alteration of habitat quality (i.e., Holtby and Scrivener 1989). A reduction in habitat quality could occur, for example, as a result of spawning substrates becoming embedded with fine materials eroded as a result of land-based activities (Platts et al. 1989, Greig et al. 2005, Opperman et al. 2005). As spawning substrates become more highly embedded, egg incubation success is reduced or eliminated (Chapman 1988). A reduction in egg incubation success through fine sediment introduction into spawning and incubation habitats could potentially result in sockeye salmon declines from a decrease in recruitment. The foregoing provides an example of why the square unit area habitat inventories referenced in preceding sections are, perhaps necessarily, a simplification of habitat status because they do not take into account habitat quality or functional contributions.

While broad data on habitat quality are not available, there are data available that suggest that Harrison Lake sockeye from both managed spawning habitats (Weaver Channel) and natural spawning habitats (Weaver Creek, Douglas Creek, Birkenhead River) have maintained higher productivity levels relative to other Fraser sockeye stocks (Grant et al. 2010). If the quality of the spawning substrate were the cause of declines, it would be expected that the stocks which continue to do well would be those stocks where egg incubation is carried out in the managed, optimum substrates available in the Weaver channel (where fines can be flushed from the gravels) relative to natural habitats (where fines cannot readily be flushed), suggesting that such impacts on spawning substrate characteristics, at least in the Harrison catchment are not presently a major factor in Harrison sockeye returns.

Recommendations for Habitat Conservation Strategies

***Project Review* –** The information obtained from this review and our experience with habitat management suggests that the habitat management strategy (based on the Act and the policy), which includes a requirement to either protect existing habitats through project design to avoid adverse impacts on habitat or to compensate habitats (typically at a 2:1 ratio) remains relevant and useful after more than two decades of experience with its implementation and suggests a net gain of habitat as a result of habitat compensation projects. Our review suggests that where this review process functions correctly, major projects can be developed without adversely impacting Fraser sockeye production and they may provide an opportunity for habitat gains (*Inset 1*).

***Habitat Science* –** Our review suggested that some earlier attempts at habitat compensation were not consistently successful. Studies carried out to review successful designs and implementation techniques resulted in effective habitat compensation and restoration projects. It is readily conceivable that in the future, physical space to construct new habitats (i.e., tidal marshes) could become constrained by available space and research into habitat compensatory design and metrics that will allow for conversion between habitat types would seem a necessity to address habitat management (and, by extension, project development) needs.

***Biological Monitoring of Constructed Habitats* –** The ability to effectively measure the success or failure of constructed and restored habitats is dependent on monitoring and evaluating habitat projects using consistent and comparable methods. Standard and robust evaluation methods would provide a scientific basis for selecting habitat compensation ratios for comparison of habitat quality and losses and gains. There is habitat monitoring being carried out at present. However, simple metrics such as the area lost and the area gained do not adequately provide data on the ecological services that have been lost or gained. Such data will have present and future benefits in managing habitat as it will also contribute to habitat science.

***Biological Monitoring of Existing Habitat* –** Data on the current status is needed to determine the quantity and quality of sockeye habitats in the lower Fraser. The data available for our review were compiled from reviewed projects or post-project review of habitat compensation success.

***Data Management Framework* –** The present manner in which physical and biological habitat data are collected (different between projects), reported and stored (hardcopy or electronic) is not readily available for analysis and use to evaluate and manage current and future habitat compensation and restoration projects and their design and implementation. The development of a data management framework for monitoring programs would provide a basis for review and evaluation of habitat projects in the future. A data management framework would necessarily require some standardization of monitoring approaches.

Section 5: Summary and Conclusion

Human development across the Georgia basin has resulted in large changes in population size and density in urban centres. Change in population reflects increasing pressures on the environment because of the potential for higher levels of water use and pollution, nutrients and contaminants from wastewater and runoff, conversion of vegetated lands (natural, forests, agricultural) to urban and industrial areas. However, during that same time, programs have been in place to curb and manage runoff and human related discharges and to manage wastes more efficiently and with reduced impacts. Population growth is therefore not a reliable predictor of worsening effect because of compensatory mechanisms (e.g. waste management) that slow down some of the population-related changes. Contaminants in the Strait of Georgia show a general improvement over time, with decreases associated with effluent regulation and improved treatment in recent years. For example, upgrades and efficiencies in the sewage collection and treatment systems in Metro Vancouver have taken place over the period of study. Some contaminants are under either control (PBDE) or study (personal care and pharmaceutical products).

The physical construction of development projects adjacent to sockeye habitats has also been regulated and there is evidence that habitat conservation efforts, through regulatory review and through restoration of habitats, have enhanced previously lost or degraded habitats and have resulted in habitat gains. Increasing population size, urban density, industrial and infrastructure development and associated land use and waste as factors in the decline of Fraser sockeye were ranked as having low to moderate (in some specific areas) potential for impacts on juvenile and adult sockeye habitats in the lower Fraser River and adult sockeye habitats in the Fraser estuary (Table 4).

In many areas where human activities and development are concentrated, sockeye often have limited residence periods in adjacent habitats. For example, the lower Fraser River and estuary are primarily used by both adult and juvenile (with some exception) sockeye over periods of days as migratory corridors. Historically (i.e., over the past century), many human activities may have had moderate to severe effects on sockeye habitats, but these impacts have not been generally observed during the last 2 decades and importantly, these impacts have not been observed to coincide with the 1990 – 2009 decline of the Fraser River sockeye. The human activities reviewed often exhibited limited spatial and temporal (duration) overlap with sockeye habitat use. In a number of instances, additional regulatory controls (discharge, waste, contaminants, agricultural and forestry practices, shipping, ballast discharge, regulatory review of project development, non indigenous species introductions), improvements to industrial and municipal practices (solid and liquid waste management), and management regimes and protocols (urban development, agricultural and forestry practices, project development, dredging, dikes) have resulted in reduced or declining potential effects and reduced interactions and risk of loss or degradation of existing sockeye habitats relative to periods prior to the last two decades. This is not necessarily the case for other fish species.

Table 4: Summary of Potential Links to Fraser Sockeye Declines Based on Interaction and Effects of Human Activities

Summary Risk of Loss or Degradation of Sockeye Habitats	General Areas of Sockeye Habitats					
	Lower Fraser Watersheds	**Lower Fraser River**	**Fraser River Estuary**	**Central Strait of Georgia**	**Northern Strait of Georgia**	**Juan de Fuca Strait**
1. Population	Low	Low	Low	Nil	Nil	Nil
2. Land use	Mod	Nil	Nil	Nil	Nil	Nil
3. Industrial and Infrastructure Projects	Nil	Low	Low	Nil	Nil	Nil
4. Waste	Nil	Low	Low	Nil	Nil	Nil
5. Shipping and Vessel Traffic	n/a	n/a	Nil	Nil	Nil	Nil
6. Dredging, Diking, Disposal at Sea	n/a	Low	Low	Nil	n/a	n/a
7. Strait of Georgia Water Properties	n/a	n/a	Low	Mod	Mod	Nil
8. Strait of Georgia Biological Properties		n/a	Nil	High	High	Nil
9. Contaminated Materials	Nil	Low	Low	Nil	Nil	Nil
10. Non Indigenous Species Introductions	Low	Low	Low	Nil	Nil	Nil

Potential interactions between biophysical conditions in the Strait of Georgia and sockeye (habitat and habitat use) are suggested as representing moderate and high risk to sockeye in the data compiled here, but limits in existing studies and data prevent an analysis of the causality of these interactions. Our review suggests that there may be an association between changes in biophysical conditions (temperature and food availability and/or quality) in the Strait of Georgia, sockeye habitat use and potentially production (Table 4). This observation is not supported by conclusive causal linkages, but is supported by other studies (see below) which suggest that Fraser sockeye production is expected to be higher when sockeye growth and condition are high, compared with poorer sockeye production in years where the sockeye have lower growth and condition. Cooler years in the Strait of Georgia are expected to result in habitats with higher abundance and availability of preferred (larger sized, higher energy content – El-Sabaawi et al. 2009a, b, 2010) sockeye prey and lower levels of competitors (c.f. Beamish et al. 2010) and predators (c.f. Beamish and Neville 2001). Relative to other factors examined in our review, changes and variation in the biophysical conditions associated with cool or warm years can be widespread and extend over large areas of sockeye habitats and extended periods of habitat use. In some seasons or years, changes in biophysical conditions and resulting sockeye food availability may have profound effects on sockeye growth and production (Beamish et al. 2004, Farley and Trudel 2009, Irvine et al. 2010; c.f. Beamish and Mahnken 2001, Beamish et al. 2010, Chittenden 2010). The observations of association in time and space between sockeye declines and water and biological conditions in the Strait as presented here, are unlikely to be soley responsible for the declines observed in the sockeye populations. The cause is likely much more complex, although the observations do suggest that research in these areas is warranted.

The habitat protection strategies used in the lower Fraser River and Strait of Georgia, appear to be effective at supporting sockeye habitat conservation during project review and project-related activities (e.g., construction impacts of a specific project). More broadly, a hypothesis that the declines in Fraser River sockeye production are the result of major (or even moderate and minor) project development is not supported by the likely net gains in habitat that have occurred over the period of review.

Overall, the development of major projects and resource restoration efforts during the period 1990 – 2010 has resulted in a net gain of sockeye habitat and these gains have been substantially added to through efforts to restore historically lost or damaged fish habitats. Maintaining active review of habitat projects is considered to be a critical habitat management approach and an important requirement for current and future activities and human development projects. Although the effectiveness of habitat compensation projects in the Fraser River appears to be improving, the need for an improved habitat science, monitoring and data management framework is clear and aspects of this need are consistent with recommendations made by others over the past decade or two. In our view, some efforts have been made in this direction, but these have not been adequate and are even less likely to be adequate into the future as the physical space to construct habitats in the manner that has been done over the past two decades decreases.

Our review has examined a subset of factors that were consistent with those identified with broad input from a variety of participants in the first phase of the Cohen Commission of Inquiry (Cohen 2010). Our review found that in many cases, the perceived causes of declines had actually seen improvements in conditions and management and protection strategies favourable to Fraser sockeye habitats during the course of the 1990 -2009 sockeye declines. We recommend that efforts to achieve improvements in those areas of salmon habitat research and management continue as suggest above. Coincident with the decline in Fraser sockeye production, however, warming waters in the Strait of Georgia were prevailing and along with those changes, there is evidence to suggest a decrease in the abundance and quality of preferred food. Given the extensive spatial scale of the observed biophysical changes within the habitats used by Fraser sockeye, the confluence of when the changes occurred relative to the Fraser sockeye decline and the mechanistic basis for an adverse effect (reduced food, lower growth and condition), these biophysical changes stand out as the most strongly inferred factors examined in our review. However, we caution that causality has not been demonstrated because the data to do so are lacking. These observations support a recommendation to explore further possible causal linkages between biophysical conditions in the Strait of Georgia, detailed Fraser sockeye habitat use and the characteristics of sockeye production as a research priority.

References

Adams M.A. and G.L. Williams. 2004. Tidal marshes of the Fraser River estuary: composition, structure, and a history of marsh creation efforts to 1997. p.147-172. *In* B.J. Groulx et al. *(eds)*. Fraser River delta, British Columbia: Issues of an urban estuary. Geological Survey of Canada Bulletin 567.

AGRA Earth & Environmental Ltd. 1996. A Description of Martin Creek Stream Habitat Enhancement Activities Completed in Fall 1996. Submitted to British Columbia Ministry of Environment, Watershed Restoration Program. 1996. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Allen S., M. Wolfe and D. Latronell. 2010. Prediction of the spring bloom in the Strait of Georgia. p.119, *In* W.R. Crawford, and J.E. Irvine [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/053.

Anonymous.1951. A Partial Reconnaissance Survey of Harrison Lake, Ministry of Sustainable Resource Management, Victoria, BC, 1951. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Augerot, X. 2005. Atlas of Pacific salmon: The first map-based status assessment of salmon in the North Pacific. State of the Salmon, Wild Salmon Centre, Portland, OR 161p.

Backman, D.C. and T.L. Simonson. 1985. The Serpentine River Watershed Salmonid Resource Studies 1984-85. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Bailey, R.E., Margolis, L. and C. Groot, C. 1988. Estimating stock composition of migrating juvenile Fraser River (British Columbia) sockeye salmon, *Oncorhynchus nerka*, using parasites as natural tags. Can. J. Fish. Aquat. Sci. 45: 586–591.

Barber, F.G. 1979. On ocean migration, speciation, cycle dominance, and density dependence in Pacific Salmon. Fisheries and Marine Service Technical Report 872, 7p.

Barber, F.G. 1983. Inshore Migration of Adult Fraser River Sockeye, A Speculation. Can. Tech. Rep. Fish. Aquat. Sci. 1162:iv+14p.

Barraclough, W.E. 1967a. Data record: number, size and food of larval and juvenile fish caught with a two boat surface trawl in the Strait of Georgia April 25–29, 1966. Manuscr. Rep. (FRBC) 922, 54 p.

Barraclough, W.E. 1967b. Data record: number, size and food of larval and juvenile fish caught with an Isaacs-Kidd trawl in the surface waters of the Strait of Georgia April 25–29, 1966. Manuscr. Rep. (FRBC) 926, 79 p.

Barraclough, W.E. 1967c. Data record: number, size composition and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia June 6–8, 1966. Manuscr. Rep. (FRBC) 928, 58 p.

Barraclough, W.E. and J.D. Fulton. 1967. Data record : number, size composition and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia July 4–8, 1966.

Barraclough, W.E. and A.C. Phillips. 1978. Distribution of juvenile salmon in the southern Strait of Georgia during the period April to July 1966–1969. Fish. Mar. Serv. Tech. Rep. 826, 47 p.

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

Beacham, T.D. 1986. Type, quantity, and size of food of Pacific salmon (*Oncorhynchus*) in the Strait of Juan de Fuca, British Columbia. U.S. Natl. Mar. Fish. Serv. Fish. Bull. 84(1):77-89.

Beamish, R.J. and C.M. Neville. 2001. Predation-based mortality on juvenile salmon in the Strait of Georgia. North Pacific Anadromous Fish Commision (NPAFC) Technical Report No. 2:11-13.

Beamish, R.J., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Prog. Oceanogr. 49: 423–437

Beamish, R.J., Pearsall I.A., and Healey M.C. 2003. A History of the Research on the Early Marine Life of Pacific Salmon Off Canada’s Pacific Coast. N. Pac. Anadr. Fish. Comm. Bull. 3:1-40.

Beamish, R.J., Schnute, J.T., Cass, A.J., Neville, C.M. and Sweeting, R.M. 2004. The influence of climate on the stock and recruitment of pink and sockeye salmon from the Fraser River, British Columbia, Canada. Trans. Am. Fish. Soc. 113: 1396–1412.

Beamish, R.J., Sweeting, R., Lange, K., Neville, C., Preikshot, D., Thomson, R. and Beacham, T. 2010. An explanation for the poor return of sockeye salmon to the Fraser River in 2009. Presentation to the PSC Workshop.

Beamish, R.J., Sweeting, R.M., Neville, C.M., and Lange, K. 2005. Changing trends in the rearing capacity of the Strait of Georgia ecosystem for juvenile Pacific salmon. (NPAFC Doc. 875) 15 p. Fisheries and Oceans Canada, Science Branch – Pacific Region, Pacific Biological Station, Nanaimo, B.C., V9T 6N7, Canada.

Beamish, R.J., Trudel, M. and Sweeting, R. 2007. Canadian Coastal High Seas Juvenile Pacific Salmon Studies. North Pacific Anadromous Fish Commision (NPAFC) Technical Report No. 7:1-4.

Beamish, R., J. Wade, W. Pennell, E. Gordon, S. Jones, C. Neville, K. Lange, and R. Sweeting. 2009. A large, natural infection of sea lice on juvenile Pacific salmon in the Gulf Island area of British Columbia, Canada. Aquaculture 297 (2009):31-37.

BIOTERRA Consulting Ltd. 1998a. Watershed and Site Level Riparian Assessment, Cogburn Creek Watershed (100-5351), Final, Prepared for: Ministry of Environment. 1998. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

BIOTERRA Consulting Ltd. 1998b. Overview and Level 1 Fish Habitat Assessment, Cogburn Creek Watershed (100-5351), Prepared for: Ministry of Environment. 1998. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Birtwell, I.K., Nassichuk, M.D. and Beune, H. 1987. Underyearling sockeye salmon (*Oncorhynchus nerka*) in the estuary of the Fraser River, pp. 25–35 *In* H.D. Smith, L. Margolis, and C.C. Wood [eds.], Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96.

Blackbourn, D.J. 1987. Sea surface temperature and pre-season prediction of return timing in Fraser River sockeye salmon (*Oncorhynchus nerka*), pp. 296–306 *In* H.D. Smith, L. Margolis, and C.C. Wood [eds.], Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96.

Boersma, L., 1990, Personal communication. Department of Fisheries and Oceans (DFO) Patrolman. Chilliwack Subdistrict. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Bradord, M.J., C.P. Tovey, and L-M. Herborg. 2008a. Biological Risk Assessment for Yellow Perch (*Perca flavescens*) in British Columbia. CSAS Research Document 2008/073.

Bradord, M.J., C.P. Tovey, and L-M. Herborg. 2008b. Biological Risk Assessment for Northern Pike (*Esox lucius*), Pumpkinseed (*Lepomis gibbosus*), and Walleye (*Sander vitreus*) in British Columbia. CSAS Research Document 2008/074.

Brannon, E.L. 1987. Mechanisms stabilizing salmonid fry emergence timing. In Sockeye salmon (Oncorhynchus nerka) population biology and future management. Edited by H.D. Smith, L. Margolis, and C.C. Wood. Can. Spec. Publ. Fish. Aquat. Sci. No. 96. pp. 120–124.

Brown, R.F. and Marshall D.D. 1979. Catalogue of Salmon Streams and Spawning Escapements of Lillooett-Pemberton Sub-District, Johnny Sandy Creek. Department of Fisheries and Oceans, Pacific Region, Environmental Services Branch.

Brown, T.J., T.R. Whitehouse, and C.D. Levings. 1989. Beach Seine Data from the Fraser River at the North Arm, Main Arm, and Agassiz During 1987-88. Can. Data Rep. Fish. Aquat. Sci. 737:134p.

Brett, J. R. 1983. Life energetics of sockeye salmon, *Oncorhynchus nerka*, pp. 29-63, *In* W. P. Aspey and S. I. Lustick [eds.] Behavioral energetics: the cost of survival in vertebrates. Ohio State University Press, Columbus.

Burgner, R.L. 1991. The life history of sockeye salmon (*Oncorhynchus nerka*), pp. 1–117 *In* C. Groot and L. Margolis [eds.], Pacific Salmon Life Histories. UBC Press, Vancouver, Canada, 564p.

Buxton, D., 1995, Personal Communication, Department of Fisheries and Oceans (DFO), Pacific Region, New Westminster, British Columbia. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Campbell, R.W., and J.F. Dower. 2008. Depth distribution during the life history of *Neocalanus plumchrus* in the strait of Georgia. Journal of Plankton Research 30: 7-20.

Canadian Environmental Assessment Agency (CEA Agency). 1999. Operational Policy Statement OPS-EPO/3-1999. Addressing Cumulative Environmental Effects under the Canadian Environmental Assessment Act (March 1999).

Cave, J.D. and W.J. Gazey. 1994. A preseason simulation model for fisheries on Fraser River sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 51: 1535-1549.

Chandler, P. 2010. Long-term temperature and salinity at BC Lighthouses. pp. 49-51 *In* W.R. Crawford, and J.E. Irvine [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/053.

Chapman DW. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Trans Am Fish Soc 117:1–21.

Chittenden1, C.M., J.L.A. Jensen, D. Ewart, S. Anderson, S. Balfry, E. Downey, A. Eaves, S. Saksida, B. Smith, S. Vincent, D. Welch, R.S. McKinley. 2010. Recent Salmon Declines: A Result of Lost Feeding Opportunities Due to Bad Timing? PLoS ONE 5(8): e12423. doi:10.1371/journal.pone.0012423

Chuchukalo, V.I., A.F. Volkov, A. Ya. Efimkin, and N.A. Kuznetsova. 1995. Feeding and daily rations of sockeye salmon (*Oncorhynchus nerka*) during the summer period. (NPAFC Doc. 125). 9p. Pacific Research Institute of Fisheries and Oceanography (TINRO), Vladivostok, 690600, Russia.

Church, M. 2010. Sediment management in the Lower Fraser River: Criteria for a sustainable long-term plan for the gravel bed reach. University of British Columbia, Vancouver, BC. 38p.

Clark, B.J. 1982. Letter, Lower Mainland Residual Cutthroat Sampling Attempt – August 1982. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Clark, C.W. and Levy, D.A. 1988. Diel vertical migrations by juvenile sockeye salmon and the antipredation window. Am. Nat. 131: 271–290.

Clearly, J.S., J.F. Schweigert, and V. Haist. 2009. Stock Assessment and Management Advice for the British Columbia Herring Fishery: 2009 Assessment and 2010 Forecasts, Canadian Science Advisory Secretariat Research Document 2009/079

Cohen, B.I. 2010. Fraser River sockeye salmon: Past declines, future sustainability? Interim Report October 2010. Commission of Inquiry into the decline of sockeye salmon in the Fraser River. Vancouver, BC, 302p.

Cooke, S.J., S.G. Hinch, A.P. Farrell, D.A. Patterson, K. Miller-Saunders, D.W. Welch, M.R. Donaldson, K.C. Hanson, G.T. Crossin, M.T. Mathes, A.G. Lotto, K.A. Hruska, I.C. Olsson, G.N. Wagner, R. Thomson, R. Hourston, K.K English, S. Larsson, J.M. Shrimpton and G. Van Der Kraak. 2008a. Developing a mechanistic understanding of fish migrations by linking telemetry with physiology, behavior, genomics, and experimental biology: an interdisciplinary case study on adult Fraser River sockeye salmon. Fisheries, 37(7): 321–338

Cooke, S.J., S.G. Hinch, G.T. Crossin, D.A. Patterson, K.K. English, M.C. Healey, J.S. Macdonald, J.M. Shrimpton, J.L. Young, A. Lister, G. Van Der Kraak, and A.P. Farrell. 2008b. Physiological correlates of coastal arrival and river entry timing in Late Summer Fraser River sockeye salmon (*Oncorhynchus nerka*). Behavioural Ecology 19: 747-758.

Crawford, W.R. and J.R. Irvine (eds.). 2009. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/022.

Crawford, W.R. and J.R. Irvine (eds.). 2010. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/053.

Crittenden, R.N. 1994. A diffusion model for the downstream migration of sockeye salmon smolts. Ecol. Modelling 71 :69-84.

Crossin GT, Hinch SG, Farrell AP, Higgs DA, Lotto AG, Oakes JD, Healey MC. 2004. Energetics and morphology of sockeye salmon: effects of upriver migratory distance and elevation. J Fish Biol. 65:788–810.

Crossin, G.T., Hinch S.G., Cooke, S.J., Welch, D.W., Batten, S.D., Patterson, D.A., Van Der Kraak, G., Shrimpton, J.M. and Farrell, A.P. 2007. Behaviour and physiology of sockeye salmon homing through coastal waters to a natal river. Mar. Biol. 152: 905–918.

Daly, E.A., Brodeur, R.D. and Weitkamp, L.A. 2009. Ontogenetic shifts in diets of juvenile and subadult coho and chinook salmon in coastal marine waters: important for marine survival? Trans. Am. Fish. Soc. 138: 1420–1438.

Davis, N.D., K.Y. Aydin, and Y. Ishida. 2000. Diel catches and food habits of sockeye, pink, and chum salmon in the central Bering Sea in summer. N. Pac. Anadr. Fish Comm. Bull. No. 2: 99–109.

Davis, N.D., M. Fukuwaka, J.L. Armstrong, and K.W. Meyers. 2005. Salmon Food Habits Studies in the Bering Sea, 1960 to Present. N. Pac. Anadr. Fish Comm. No. 2:24-28.

deBruyn, A.M.H., L.M. Meloche, and C.J. Lowe. 2009. Patterns of Bioaccumulation of Polybrominated Diphenyl Ether and Polychlorinated Biphenyl Congeners in Marine Mussels Environ. Sci. Technol. 43 (10), 3700-3704

DFO (Fisheries and Oceans Canada). [No date]. Stream files Squamish office, DFO – Sub-District 28B: Squamish. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

DFO (Fisheries and Oceans Canada). 1986. National Policy for the Management of Fish Habitat. Ottawa, ON. 1986.

DFO (Fisheries and Oceans Canada). 1988. Data Form, Stream Summary Catalogue Subdistrict #29C Coquitlam, 1988. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

DFO (Fisheries and Oceans Canada). 1999. Lower Fraser Valley Streams Strategic Review Lower Fraser Valley Stream Review, Vol. 1. Fraser River Action Plan, Fisheries and Oceans Canada, Vancouver, BC. 487p.

DFO (Fisheries and Oceans Canada). 2002. Cultus Lake sockeye recovery planning process. Report of the Stock Assessment and Fisheries Management Work Group. July 24, 2002. Fisheries and Oceans Canada, Vancouver, BC. 101p.

DFO (Fisheries and Oceans Canada). 2010. Assessment of Cultus Lake Sockeye Salmon in British Columbia in 2009 and Evaluation of Recent Recovery Activities. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/056.

DFO (Fisheries and Oceans Canada). 2002. 2002 Pacific Region State of the Ocean. Ocean Status Report, Fisheries and Oceans Canada, Pacific Region, Vancouver, BC, 54p.

DFO (Fisheries and Oceans Canada). 2003. 2003 Pacific Region State of the Ocean. Ocean Status Report 2004, Fisheries and Oceans Canada, Pacific Region, Vancouver, BC, 92p.

DFO (Fisheries and Oceans Canada). 2009. State of the Pacific Ocean 2008. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/030.

DFO (Fisheries and Oceans Canada). 2010. State of the Pacific Ocean 2009. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/034.

Diewert, R.E., and M.A. Henderson. 1992. The effect of competition and predation on production of juvenile sockeye salmon (*Oncorhynchus nerka*) in Pitt Lake. Can. Tech. Rep. Fish. Aquat. Sci. 1853: 51 p.

Dunford, W. E. 1975. Space and food utilization by salmonids in marsh habitats of the Fraser River Estuary. MS Thesis, University of British Columbia. 81 p.

Duval, W.S. 1975a, A Reconnaissance Survey of Chilliwack Lake. Ministry of Environment (formerly Ministry of Sustainable Resource Management). *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Duval, W.S. 1975b, A Reconnaissance Survey of Widgeon Lake. Ministry of Environment (formerly Ministry of Sustainable Resource Management). *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Elliott, J.E., L.K. Wilson, and B. Wakeford. 2005. Polybrominated diphenyl ether trends in eggs of marine and freshwater birds from British Columbia, Canada. Environ. Sci. Technol. 39(15):5584-91.

Ellis, E., M. Church and M. Rosenau. 2004. Characterisation of four secondary channels of the Lower Fraser River. Habitat Conservation Trust Fund – Final Report. Vancouver, BC. 186p.

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

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

El-Sabaawi, R., A.R. Sastri, J.F. Dower, and A. Mazumder. 2010. Deciphering the Seasonal Cycle of Copepod Trophic Dynamics in the Strait of Georgia, Canada, Using Stable Isotopes and Fatty Acids. Estuaries and Coasts 33:738–752

Elson, M.S., M. Graves, and Pugh, J.D. 1986. A Review of International Pacific Salmon Fisheries Commission Bioreconnaissance Data, with Reference to Proposed Fraser River system Sockeye and Pink Salmon Enhancement Projects. Prepared for SEP, New Projects Unit. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Elvidge, R. 1986. Personal Information. Technical Officer, Fisheries and Oceans Canada, Habitat Management, New Westminster. 1986. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

English K, Sliwinski C, Labelle M, Koski WR, Alexander R, Cass A, Woodey J. 2004. Migration timing and in-river survival of late-run Fraser River sockeye using radio-telemetry techniques. Report prepared by LGL Limited, Sidney, BC for the Pacific Biological Station of Fisheries and Oceans, Canada

Farley E.V, and M. Trudel. 2009. Growth rate potential of juvenile sockeye salmon in warmer and cooler years on the eastern Berring sea shelf. Journal of Marine Biology 2009:1-10.

Farwell, M.K. [no date]. Fraser River, Howe Sound, Burrard Inlet, Indian Arm and Boundary Bay Salmon Escapements. Can. Data Rep. Fish. Aquat. Sci.(in prep.). *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Federal Environmental Assessment Review Office (FEARO). 1994. Reference Guide – Determining Whether a Project is Likely to Cause Significant Environmental Effects. Federal Environmental Assessment Review Office, Ottawa, ON.

Fedorenko, A.Y. 1984. Physical and biological comparison of Chilliwack-Vedder tributaries. Fisheries and Oceans Canada (DFO), Unpublished report. Draft #2. August 1984. 30p + appendices. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Foerster, R.E. 1968. The sockeye salmon, *Oncorhynchus nerka*. Bull. Fish. Res. Bd. Can. 162, 422p.

Fraser, D.A., J.K. Gaydos, E. Karlsen and M.S. Rylko. 2006. Collaborative science, policy development and program implementation in the transboundary Georgia Basin / Puget Sound Ecosystem. Envir. Monitoring and Assessment 113:49-69

Fraser River Estuary Management Program (FREMP). 2002. Estuary Management Plan: Fish and Wildlife Habitat. http://www.bieapfremp.org/fremp/managementplan/actionareas_fish.html (Accessed January 2011).

Fraser River Estuary Management Program (FREMP). 2006. Environmental management strategy for dredging in the Fraser River estuary. Vancouver, BC. 47p.

Gable, J. and S. Cox-Rogers. 1993. Stock Identification of Fraser River Sockeye Salmon: Methodology and Management Application. Pacific Salmon Comm. Tech. Rep. No. 5. 36p.

Gardner, G.A. 1977. Analysis of zooplankton population fluctuations in the Strait of Georgia, British Columbia. Journal of the Fisheries Research Board of Canada, 34:1196-1206.

Gilhousen P. 1960. Migratory behaviour of adult Fraser River sockeye. 778

Gillespie, G.E., 2007. Distribution of non-indigenous intertidal species on the Pacific Coast of Canada. Nippon Suisan Gakkaishi 73(6): 1133-1137

Gillespie, G.E., A.C. Phillips, D.L. Paltzat, and T.W. Therriault. 2006. Distribution of non-indigenous intertidal species on the Pacific Coast of Canada. PICES 15th Annual Meeting, Boundary current ecosystems. Session 8. October 13-22, 2006, Yokohama, Japan.

Gower, J., and S. King. 2010. Remote sensing of chlorophyll in the Strait of Georgia. p.118. *In* W.R. Crawford, and J.E. Irvine [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/053.

Grant, S.C.H., C.G.J. Michielsens, E.J. Porszt, and A. Cass. 2010. Pre-season run size forecasts for Fraser River Sockeye salmon in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/042.

Greer, G.L., C.D. Levings, R. Harbo, B. Hillaby, T. Brown, J. Sibert. 1980. Distribution of Fish Species on Roberts Bank and Sturgeon Banks recorded in seine and trawl surveys. Can. MS Rep. Fish. Aquat. Sci. 1596: 51p.

Gregory, R.S. and C.D. Levings. 1996. The effects of turbidity and vegetation on the risk of juvenile salmon (*Oncorhynchus* spp.) to predation by adult trout (*O. clarkii*). Environmental Biology of Fishes 47(3): 279-288

Gregory, R.S. and C.D. Levings 1998. Turbidity reduces predation on migrating juvenile Pacific salmon. Trans Amer Fish Soc 127: 275-285

Gregory, R.S., T.R. Whitehouse, and C.O. Levings . 1993. Beach seine catches, lengths, weights, and stomach content data of salmonids and other fishes from the Harrison and Fraser Rivers, April and May 1991. Can. Data Rep. Fish. Aquat. Sci. 902: 85 p.

Greig, S.M., D.A. Sear and P.A. Carling. 2005. The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management. Science of the Total Environment 344:241– 258

Groot C. 1982. Modifications on a theme - a perspective on migratory behaviour of Pacific salmon. ***In*** E.L. Brannon and E.O. Salo (Eds.). Proceedings of the Salmon and Trout Migratory Behaviour Symposium. School of Fisheries. Univeristy of Washington, Seattle, WA. pp. 1-21.

Groot, C., R.E. Bailey, L., Margolis, L., and K. Cooke. 1989. Migratory patterns of sockeye salmon (Oncorhynchus nerku) smolts in the Strait of Georgia, British Columbia, as determined by analysis of parasite assemblages. Can. J. Zool. 67: 1670-1678.

Groot, C. and Cooke, K., 1987. Are the migrations of juvenile and adult Fraser River sockeye salmon (*Oncorhynchus nerka*) in near-shore waters related? pp. 53–60 *In* H.D. Smith, L. Margolis, and C.C. Wood [eds.], Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Pub. Fish. Aquat. Sci. 96.

Groot, C., K. Cooke, G. Ellis, and R. Bailey. 1985. Data record of juvenile sockeye salrnon and other fish species captured by purse seine and trawl in the Strait of Georgia, Johnstone Strait and

Queen Charlotte Strait in 1982, 19l:l3, 1984, and 1985. Can. Data Rep. Fish. Aquat. Sci. No. 561: 147 p.

Groot, C. and Margolis, L. 1991. Pacific salmon life histories. UBC Press: Vancouver, Canada, 564 p.

Groot, C. and Quinn, T.P. 1987. Homing migration of sockeye salmon, *Oncorhynchus nerka*, to the Fraser River. Fish. Bull. 85: 455–469.

Haegele, C.W. 1997. The Occurrence, Abundance and Food of Juvenile Herring and Salmon in the Strait of Georgia, British Columbia in 1990 to 1994. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2390. 124p.

Haegele, C.W., D.E. Hay, J.F. Schweigert, R.W. Armstrong, C.Hrabok, M.Thompson, and K.Daniel, 2005. Juvenile Herring Surveys in Johnstone and Georgia Straits - 1996 to 2003. Canadian Data Report of Fisheries and Aquatic Sciences 1171.243p.

Ham, D. and Church, M. 2002. Channel island and active channel stability in the lower Fraser River gravel reach. Report prepared for the City of Chilliwack by Dept. of Geography, University of British Columbia.

Hamilton, K. 1985. A study of the return migration route of Fraser River sockeye salmon (*Oncorhyncus nerka*). Can. J. Zool. 63: 1930–1943.

Haro-Garay, M.J., and L.H. Soberanis. 2008. Dominance shift of zooplankton species composition in the central Strait of Georgia, British Columbia during 1997. Hidrobiologica 18 (Suplemento): 53-60.

Harper, D.J., and J.T. Quigley. 2005. A comparison of the areal extent of fish habitat gains and losses associated with selected compensation projects in Canada. Fisheries 30(2):18-25.

Harris, M.L., J.E. Elliott, R.W. Butler, and L.K. Wilson. 2003. Reproductive success and chlorinated hydrocarbon contamination of resident great blue herons (*Ardea Herodias*) from coastal British Columbia, Canada, 1977 to 2000. Environ. Pollution 121:207-227

Harris, M.L., L.K. Wilson, J.E. Elliott. 2005. An assessment of PCBs and OC pesticides in eggs of double-crested (*Phalacrocorax auritus*) and pelagic (*P. pelagicus*) cormorants from the west coast of Canada, 1970 to 2002. Ecotoxicology 14(6): 607-625

Harrison, P.J., Fulton, J.D., Taylor, F.J.R. and T.R. Parsons. 1983. Review of the biological oceanography of the Strait of Georgia: pelagic environment. Canadian Journal of Fisheries and Aquatic Sciences, 40:1064-1094.

Hartman, G.F. and M. Miles. 1995. Evaluation of fish habitat improvement projects in BC and recommendations on the development of guidelines for future work. BC Ministry of Environment Lands and Parks. 39p.

Hatfield Consultants Ltd. 1996. Strait of Georgia fisheries sustainability review. West Vancouver, BC, 441p.

Hay, D.E., J.F. Schweigert, M. Thompson, C.W. Haegele, and P. Midgley. 2003. Analyses of juvenile surveys for recruitment prediction in the Strait of Georgia. Can. Sci. Adv. Secretariat Research Document 2003/107.

Healey, M.C. 1978. The distribution, abundance, and feeding habits of juvenile Pacific salmon in Georgia Strait, British Columbia. Fish. Mar. Serv. Tech. Rep. No. 788. 49p.

Henderson, M.A. and Cass, A.J. 1991. Effect of smolt size on smolt-to-adult survival of Chilko Lake sockeye salmon (*Oncorhynchus nerka*). Can J. Fish. Aquat. Sci. 48: 988–994.

Henderson, M.A., Diewert, R.E., Hume, J., Shortreed, K., Levy, D., and Morton, K. 1991. The Carrying Capacity of Pitt Lake for Juvenile Sockeye Salmon (Oncorhynchus nerka). Can. Tech. Rep. Fish. Aquat. Sci. 1797: 161p.

Herunter, H., Seacology, N.W., and Swanston, D. 1989. Juvenile Salmonid Utilization of Camp Slough, Chilliwack, BC, 1989. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Hill, P.R., K. Conway, D.G. Lintern, S. Meulé, K. Picard, and J.V. Barrie. 2008. Sedimentary processes and sediment dispersal in the southern Strait of Georgia, BC, Canada. Marine Environmental Research 66(2008):S39-S48

Hinch S.G., S.J. Cooke, M.C. Healey, and A.P. Farrell. 2005. Behavioural physiology of fish migrations: salmon as a model approach. In: Sloman KA, Wilson RW, Balshine S, editors. Fish physiology series, Vol. 24, Behaviour and physiology of fish. New York: Academic Press. p. 239–295.

Holtby, L.B. and K.A. Ciruna. 2007. Conservation units for Pacific salmon under the Wild Salmon Policy. CSAS Res. Doc. 2007-070. 350pp.

Holtby, L.B. and J.C. Scrivener. 1989. Observed and simulated effects of climate variability, clear cut logging and fishing on the numbers of chum salmon (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) returning to Carnation Creek, British Columbia, p.62-81. *In* C.D. Levings, L.B. Holtby, M.A. Henderson [ed.] Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks. Can. Spec. Publ. Fish. Aquat. Sci. 105

Houtman, R., J.A. Tadey, and N.D. Schubert. 2000. Estimation of the 1995 Birkenhead River sockeye salmon (Oncorhynchus nerka) escapement. Can. Manuscr. Rep. Fish. Aquat. Sci. 2534: 39 p.

IPSFC (International Pacific Salmon Fisheries Commision). 1972. Proposed program for restoration and extension of the sockeye and pink salmon stocks of the Fraser River. 91p. 1972. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Interior Reforestation Co. Ltd. 1998. Alouette River Salmonid Smolt Migration Enumeration: 1998 Data Report and Water Quality, Flow and Invertebrate Study of the Alouette River Watershed. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Irvine, J.R. and Crawford, W.R. [eds.] 2008. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/013.

Irvine, J.R., Godbout, L., Brown, L., Borstad, G., Mackas, D. and Thomson, R. 2010. Do marine conditions in Queen Charlotte Sound limit the marine survival of Chilko sockeye salmon?, p. 132 *In* W.R. Crawford and J.R. Irvine [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 20108/053.

Jgermes, T. 1975. Untitled Report: Fisheries Data for Cultus Lake. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Johannes, M.R.S. 2011. Pacific Salmon Resources in Northern British Columbia and Yukon Transboundary Rivers. Vancouver, BC: Pacific Fisheries Resource Conservation Council.71p.

Johannessen, D.I. and P.S. Ross. 2002. Late-run sockeye at risk: an overview of environmental contaminants in Fraser River salmon habitat. Can. Tech. Rep. Fish. Aquat. Sci. 2429: x + 108p.

Johannessen S.C., R.W. Macdonald, and D.W. Paton. 2003. A sediment and organic carbon budget for the greater Strait of Georgia. Estuar. Coast Shelf Sci. 56:845–860

Johannessen S.C., R.W. Macdonald, C.A. Wright, B. Burd, D.P. Shaw, A. van Roodselaar. 2008a. Joined by geochemistry, divided by history: PCBs and PBDEs in Strait of Georgia sediments. Mar. Environ. Res. 66:S112–S120

Johannessen, S.C., G. Potentier, C.A. Wright, D. Masson, D. and R.W. Macdonald. 2008b. Water column organic carbon in a Pacific Marginal sea (Strait of Georgia, Canada). Marine Environmental Research, 66:49-61.

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

Johannessen, S. C. and McCarter, B. 2010. Ecosystem Status and Trends Report for the Strait of Georgia Ecozone. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/010. vi + 43 p.

Kalnin, L. 1994. Untitled, Personal Communication, Fisheries and Oceans Canada (DFO), Management Biology Unit, New Westminster, BC. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Karpenko, V.I., and L.V. Piskunova. 1984. Importance of macroplankton in the diet of young salmons of Genus *Oncorhynchus* (Salmonidae) and their trophic relationships in the southwestern Bering Sea. Vopr. Ichthiologii 24(5): 98–106.

Karpenko V.I., L.V. Piskunova and M.V. Kovai. 1998. Forage base and feeding of Pacific salmon in the sea. N. Pac. Anadr. Fish Comm. Tech. Report No. 36-38.

Kolody, D. and Healey, M.C. 1998. Numerical simulations of Fraser River sockeye salmon homing migration routes in a dynamic marine environment. N. Pac. Anadr. Fish. Comm. Bull. 1:118–128.

Kistritz, R.U. 1996. Habitat compensation, restoration, and creation in the Fraser River estuary: Are we achieving a no-net-loss of fish habitat? Can. Tech. Rept. Fish. Aquat. Sci. 2349. 70p

King J.R., and G.A. McFarlane. 2006. Shift in the size-at-age of the Strait of Georgia population of Pacific hake (*Merluccius productus*). CCOFI Rep 47:111–118

Labelle, M. 2009. Status of Pacific salmon resources in southern British Columbia and the Fraser River Basin. Pacific Fisheries Resource Conservation Council, Vancouver, BC, 91p.

Lario, G.R., Personal Communication (Stream Files), Fisheries Guardian. Mission Subdistrict. 1986. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Larson, M.R., M.G.G. Foreman, C.D. Levings, and M.R. Tarbotton. 2003. Dispersion of discharged ship ballast water in Vancouver Harbour, Juan De Fuca Strait, and offshore of the Washington Coast. J. Environ. Eng. Sci. 2:163-176

LeBrasseur, R.J. 1965. Stomach contents of salmonids caught in the northeastern Pacific Ocean, 1958. Circular. Statistical series, Fish. Res. Bd. Can., Biological Station, Nanaimo, B.C., 15, Vol. 1.

LeBrasseur, R.J. 1966. Stomach contents of salmon and steelhead trout in the Northeastern Pacific Ocean. J. Fish. Res. Bd. Can. 23: 85–100.

LeBrasseur, R.J., Barraclough, W.E., Kennedy, O.D. and Parsons, T.R. 1969. Production studies in the Strait of Georgia. Part III. Observations on the food of larval and juvenile fish in the Fraser River plume, February to May, 1967. J. Exp. Mar. Biol. Ecol. 3: 51–61.

LeBrasseur, R.J. and Doidge, D.A. 1966a. Stomach contents of salmonids caught in the northeastern Pacific Ocean, 1962. Circular. Statistical series, Fish. Res. Bd. Can., Biological Station, Nanaimo, B.C., 20, Vol. 2.

LeBrasseur, R.J. and Doidge, D.A. 1966b. Stomach contents of salmonids caught in the northeastern Pacific Ocean, 1956 and 1957. Circular. Statistical series, Fish. Res. Bd. Can., Biological Station, Nanaimo, B.C., 20, Vol. 3.

LeBrasseur, R.J. and Doidge, D.A. 1966c. Stomach contents of salmonids caught in the northeastern Pacific Ocean, 1959 and 1960. Circular. Statistical series, Fish. Res. Bd. Can., Biological Station, Nanaimo, B.C., 21, Vol. 4.

LeBrasseur, R.J. and Doidge, D.A. 1966d. Stomach contents of salmonids caught in the northeastern Pacific Ocean, 1963 and 1964. Circular. Statistical series, Fish. Res. Bd. Can., Biological Station, Nanaimo, B.C., 23, Vol. 5.

Levings, C.D. 1985. Juvenile salmonid use of habitat altered by a coal port in the Fraser River estuary, British Columbia. Marine Pollution Bulletin 16(6):248-254.

Levings, C.D. 1991. Strategies for restoring and developing fish habitats in the Strait of Georgia—Puget Sound Inland Sea, northeast Pacific Ocean. Marine Pollution Bulletin 23:417-422.

Levings, C.D. 1994. Feeding behaviour of juvenile salmon and significance of habitat during estuary and early sea phase. Nordic Journal of Freshwater Research 69: 7-16.

Levings, C.D., 1998 Functional assessment of created, restored, and replaced fish habitat in the Fraser River estuary p. 451-457 *in* Strickland, R., A.E. Copping, and N.J. Lerner (eds.). Puget Sound Research '98: Proceedings of the 1998 Puget Sound Research Conference, Seattle, WA, March 12-13, 1998 Puget Sound Water Quality Action Team, Olympia, WA. (http://www.wa.gov/puget_sound/98_proceedings/pdfs/4a_levings.pdf)

Levings, C.D., I.K., Birtwell, and G.E. Piercey. 2003. Beach Seine Catch Data from Sechelt Inlet and Agamemnon Channel, British Columbia, Can. Data Rep. Fish. Aquat. Sci. 1110:iii+23p.

Levings, C.D., D.E. Boyle and T.R. Whitehouse, 1995. Distribution and feeding of juvenile Pacific salmon in freshwater tidal creeks of the lower Fraser River, British Columbia. Fisheries Management and Ecology 2:299-308.

Levings, C.D., J.R. Cordell, S. Ong, and G.E. Piercey. 2004. The origin and identity of invertebrate organisms being transported to Canada's Pacific coast by ballast water. Canadian Journal of Fisheries and Aquatic Sciences; 61: 1-11.

Levings, C.D., G.L. Greer, and P. Miller. 1983. Results of preliminary mark-recapture experiments with juvenile salmonids on Sturgeon and Roberts Bank, Fraser River estuary. Can. MS. Rep. Fish. Aquat. Sci. 1684: iii+27p.

Levings, C.D., D. Kieser, G.S. Jamieson. and S. Dudas. 2002. Marine and estuarine alien species in the Strait of Georgia, British Columbia. pp. 111-131. In: Claudia, R., P. Nantel, and E. Mucklealeffs (eds). Alien invaders in Canada's waters, wetlands, and forests. Natural Resources Canada, Canadian Forest Service, Ottawa. 320 pp.

Levings, C.D. and M. Kotyk. 1983. Results of Two Boat Trawling for Juvenile Salmonids in Discovery Passage and Nearby Channels, northern Strait of Georgia, Can. MS. Rep. Fish. Aquat. Sci. 1730: 55p

Levings, C.D. and J.S. MacDonald. 1991. Rehabilitation of estuarine fish habitat at Campbell River, British Columbia. American Fisheries Society Symposium 10:176-190.

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

Levings, C.D., R.B. Turner, and B. Ricketts. 1992. Proceedings of the Howe Sound Environmental Science Workshop. Can. Tech. Report Fisheries and Aquatic Sciences. 1879. 270p.

Levy, D.A. 1987. Review of the ecological significance of diel vertical migrations by juvenile sockeye salmon (*Oncorhynchus nerka*), pp. 44–52 *In* H.D. Smith, L. Margolis, and C.C. Wood [eds.], Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96.

Levy, D. A. 1990. Sensory mechanism and selective advantage for die1 vertical migration in juvenile sockeye salmon, *Oncorhynchus nerka*. Can. J. Fish. Aquat. Sci. 47: 1796-1802.

Levy, D.A., G.J. Birch, and T.G. Northcote, 1979. Juvenile Salmon Utilization of Tidal Channels in the Fraser River Estuary, British Columbia, Westwater Research Centre, University of British Columbia, Vancouver, BC. Technical Report No. 23.

Levy, D.A. and Cadenhead 1995. Selective tidal stream transport of adult sockeye (*Oncorhynchus nerka*) in the Fraser River Estuary, Can. J. Fish. Aquat. Sci. 52:1-12.

Levy, D.A., P.A. Nealson, and P. Cheng. 1991. Fixed-Aspect Hydroacoustic Estimation of Fraser River Sockeye Salmon Abundance and Distribution at Mission, B.C. in 1986. PSC Tech. Rep. No. 4, October, 1991.

Levy, D.A., and T.G. Northcote. 1981. The distribution and abundance of juvenile salmon in marsh habitats of the Fraser River estuary. University of British Columbia, Westwater Research Centre, Tech. Rep. No. 25. 117p.

Levy, D.A. and T.G. Northcote. 1982. Juvenile salmon residency in a marsh area of the Fraser River Estuary. Can. J. Fish. Aquat. Sci. 39: 270-276.

Levy, D.A., T.G. Northcote, and G.J. Birch. 1979. Juvenile salmon utilization of tidal channels in the Fraser River estuary British Columbia. University of British Columbia, Westwater Research Centre, Tech. Rep. No. 23. 70p.

Lewis, A., 1994. Personal communication with fisheries officer, Fisheries and Oceans Canada (DFO), Mission Subdistrict, Mission, BC, 1994.

Lichatowich, J. 1999. Salmon Without Rivers: A History of the Pacific Salmon Crisis. Washington, D.C.: Island Press, 317 pp

McDaniels, T., S. Wilmot, M. Healey, and S. Hinch. 2010. Vulnerability of Fraser River sockeye salmon to climate change: A life cycle perspective using expert judgments. Journal of Environmental Management 91:2771-2780.

McKinnell, S.M., E. Curchitser, C. Groot, M. Kaeriyama and K.W. Myers. 2011. The decline of Fraser River sockeye salmon *Oncorhynchus nerka* (Steller, 1743) in relation to marine ecology. PICES Advisory Report. Cohen Commission Tech. Rep. 4. *In prep*. Vancouver, B.C. www.cohencommission.ca

McKinnell, S.M., Freeland, H.J. and Groulx, S. 1999. Assessing the northern diversion of sockeye salmon returning to the Fraser River. Fish. Oceanogr. 8: 104–114.

McMynn, R.G. 1953. The Water Problem on the Alouette River. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Macdonald, J.S. 2000. Mortality during the migration of Fraser River sockeye salmon (*Oncorhynchus nerka*): a study of the effect of ocean and river environmental conditions in 1997. Can. Tech. Rep. Fish. Aquat. Sci. 2315: 120p.

Macdonald, V.I., S.C. Byers, B. Budenski, and P. Hoover. 2000. Reconnaissance study to determine presence of marine exotic species in the Georgia Strait Basin. Prepared for DFO Science Branch, West Vancouver Laboratory by Biologica Environmental Services, Victoria, BC 41 pp.

MacIsaac, E.A. (editor). 2003. Forestry impacts on fish habitat in the northern interior of British Columbia: a compendium of research from the Stuart-Takla Fish/Forestry Interaction Study. Can. Tech. Rep. Fish. Aquat. Sci. 2509.

Mackas, D.L. and M. Galbraith. 2010. Fisheries and Oceans Canada, Personnel communication. Email correspondence, Dec. 23, 2010.

Mackas, D.L., S. Batten, and M. Trudel. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. Prog. Oceanogr. 75: 223–252.

Mackas, D.L., M. Galbraith, and D. Faust. 2009. Zooplankton community returns to ‘cool-ocean’ pattern off Vancouver Island, pp. 62–67, *In* W.R. Crawford and J.R. Irvine [eds.] 2009. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022. vi + 121 p.

Mackas, D.L. and P.J. Harrison. 1997. Nitrogenous nutrient sources and sinks in the Juan de Fuca Strait/Strait of Georgia/Puget Sound estuarine system: assessing the potential for eutrophication. Estuarine, Coastal, and Shelf Science, 44:1-21.

Mackas, D.L., W.T. Peterson, M.D. Ohman, and B.E. Lavaniegos. 2006. Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005. Geophys. Res. Lett. 33, L22S07.

Mackas, D.L., R.E. Thomson, and M. Galbraith. 2001. Changes in the zooplankton community of the British Columbia continental margin, and covariation with oceanographic conditions, 1985-1998. Can. J. Fish. Aquat. Sci. 58: 685–702.

Marshall, D.E., R.F. Brown, M.M. Musgrave and D.G. Demonties. 1979. Preliminary catalogue of salmon streams and spawning escapement of statistical area 29. Fisheries Marine Service Data Report 115: 73p.

Marshall, D.E., and M.J. Hancock. 1985. Catalogue of salmon streams and spawning escapements of Statistical Area 29 Mission-Harrison. Can. Data Rep. Fish and Aquat.Sci. 518: xiv + 117p. 1985. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Marshall, D.E., Manzon, C.I. and Britton, E.W. 1980. Catalogue of salmon streams and spawning escapements of Chilliwack/Hope Subdistrict. Can. Data Rep. Aquat. Sci. 203:167p.

Masson D., and P.F. Cummins. 2007. Temperature trends and interannual variability in the Strait of Georgia, British Columbia. Cont Shelf Res 27:634–649

Masson, D. 2002. Deep water renewal in the Strait of Georgia. Estuar. Coast. Shelf Sci. 54: 115–126.

Masson, D. 2008. Cooling in the Strait of Georgia, pp. 93, *In* J.E. Irvine and W.R. Crawford [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/013.

Masson, D. 2009. Cooling in sub-surface Strait of Georgia waters, pp. 107 *In* J.E. Irvine and W.R. Crawford [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022.

Melnychuk, M.C., D.W. Welch and C.J. Walters. 2010. Spatio-temporal migration patterns of Pacific salmon smolts in rivers and coastal marine waters. PLoS ONE September 2010 5(9):1-15

MELP (Ministry of Environment, Lands and Parks). 1995a. Fisheries Files: Inventory; Enhancement; Biophysical Data; and Records of Personal Communication, Fisheries Branch, Ministry of Environment, Lands and Parks, Surrey, BC. 1995. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

MELP (Ministry of Environment, Lands and Parks). 1995b. SISS Map Information, 1995. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

MELP (Ministry of Environment, Lands and Parks). 1996. Conditional Assessment of the Lillooet River Watershed, Consultant Report, Ministry of Environment, Lands and Parks. 1996. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

MELP (Ministry of Environment, Lands and Parks). [No date]. The Resource Information Index in Region II (RII) Based on VUTM 1,000 metre rectangular grid, Catalogues resource information, from referrals, inventory, studies etc., Ministry of Environment, Region 2, Surrey, BC. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Metro Vancouver. 2010a. Integrated Solid Waste and Resource Management and Solid Waste Management Plan for the Greater Vancouver Regional District and Member Municipalities. Metro Vancouver, Burnaby, BC 38p.

Metro Vancouver. 2010b. Metro Vancouver Liquid Waste Management Plan July 2010 Biennial Report. Metro Vancouver, Burnaby, BC 108p.

MOE (Ministry of the Environment), 1986. Personal communication, Culturist- Fraser Valley Trout Hatchery-Abbotsford Subdistrict, Ministry of the Environment. 1986. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

MOE (Ministry of the Environment) 2006a. British Columbia Coast and Marine Environment Project 2006: population and economic activity. Ministry of the Environment, Vancouver. Available at: http://www.env.gov.bc.ca/soe/bcce/01_population_economic/technical_paper/population_economic_activity.pdf

MOE (Ministry of Environment). 2006b. BC Municipal Solid Waste Tracking Report. 2006, Ministry of Environment, Victoria. http://www.env.gov.bc.ca/epd/epdpa/mpp/pdfs/tracking-rpt2006.pdf

MOE (Ministry of the Environment). 2006c. British Columbia Coast and Marine Environment Project 2006: Industrial Contaminants. Ministry of the Environment, Vancouver. Available at: http://www.env.gov.bc.ca/soe/bcce/02_industrial_contaminants/technical_paper/industrial_contaminants.pdf

MOE (Ministry of the Environment). 2006d. British Columbia Coast and Marine Environment Project 2006: Biodiversity. Ministry of the Environment, Vancouver. Available at: http://www.env.gov.bc.ca/soe/bcce/05_biodiversity/technical_paper/biodiversity.pdf

Montgomery, D.R. 2003. King of fish: the thousand-year run of salmon. Boulder, Colo. : Westview Press. 290 pp.

MSRM (Ministry of Sustainable Resource Management), 1984. RAB / 092G10001A, FHIIP Stream Survey Form, Ministry of Sustainable Resource Management, Victoria, BC, 1984. *In* FISS Fish

Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Mueller, C.W. and H.J. Enzenhofer 1991. Trawl Catch Statistics in Sockeye Rearing Lakes of the Fraser River Drainage Basin: 1975-1985. Can. Data Rep. Fish. Aquat. Sci. 825: 204p.

Mueller, C.W., H.J. Enzenhofer and J.M.B. Hume. 1991. Trawl Catch Statistics from Seven Sockeye Rearing Lakes of the Fraser River Drainage Basin: 1986-1991. Can. Data Rep. Fish. Aquat. Sci. 864: 87p.

Northcote, T.G. 1951. A Reconnaissance Survey of Cultus Lake, Technical Report, 1951. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

NHC (Northwest Hydraulics Consultants). 2008. Comprehensive review of Fraser River at hope Flood hydrology and flow scoping study – Final Report. Ministry of Environment, Victoria, BC. 63p.

NHC (Northwest Hydraulics Consultants). 2009. Fraser River sediment budget. Phase 2 – Final Report. Emergency Management BC, Victoria, BC. 20p. + Figures and Appendices.

NHC (Northwest Hydraulic Consultants) and Triton Consultants Ltd. 2006. Lower Fraser River Hydraulic Model – Final Report. Prepared for the Fraser Basin Council. 243p.

Opperman, J.J., K.A. Lohse, C. Brooks, N.M. Kelly, and A.M. Merenlender. 2005. Influence of land use on fine sediment in salmonid spawning gravels within the Russian River Basin, California. Can. J. Fish. Aquat. Sci. 62: 2740–2751

Parsons, T.R., Stephens, K. and LeBrasseur, R.J. 1969a. Production studies in the Strait of Georgia. Part I. Primary production under the Fraser River plume, February to May, 1967. J. Exp. Mar. Biol. Ecol. 3: 27–38.

Parsons, T.R., LeBrasseur, R.J., Fulton, J.D. and Kennedy, O.D. 1969b. Production studies in the Strait of Georgia. Part II. Secondary production under the Fraser River plume, February to May, 1967. J. Exp. Mar. Biol. Ecol. 3: 39–50.

Pascual, M.A. and T.P. Quinn. 1991. Evaluation of alternative models of the coastal migration of adult Fraser River sockeye salmon (*Oncurhynchus nerka*). Can. J. Fish. Aquat. Sci. 48: 799-8 10.

Pearson, M. and L. Chiavaroli. 2010. Harrison River Watershed Habitat Status Report, Prepared for Fisheries and Oceans Canada, Prepared by Balance Ecological Environmental Consultants, May 10, 2010.

Pena, A. 2008. Phytoplankton in the Strait of Georgia. pp. 94-95, *In* J.E. Irvine and W.R. Crawford [eds.] 2008. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/013.

Pena, A. 2010. Phytoplankton in the Strait of Georgia. pp. 115-117. *In* W.R. Crawford, and J.E. Irvine [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/053.

Pearson and Chiavaroli 2010. Harrison River Watershed Habitat Status Report, Prepared for Fisheries and Oceans Canada, Prepared by Balance Ecological Environmental Consultants, May 10, 2010.

Peterman, R.M., Marinone, S.G., Jardine, I.D., Crittenden, R.N., LeBlond, P.H. and Walters, C.J. 1994. Simulation of juvenile sockeye salmon (*Oncoryhnchus nerka*) migrations in the Strait of Georgia, British Columbia. Fish. Oceanogr. 3:221–235.

Peterman R.M., D. Marmorek, B. Beckman, M. Bradford, N. Mantua, B.E. Riddell, M. Scheuerell, M., Staley, K. Wieckowski, J.R. Winton, and C.C. Wood. 2010. Synthesis of evidence from a workshop on the decline of Fraser River sockeye. June 15–17, 2010. A Report to the Pacific Salmon Commission, Vancouver, B.C. 246p.

Peters, K. 1994. Personal communication with Ken Peters, Fisheries and Oceans Canada (DFO), Pacific Region, Project Supervisor Operations Branch. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Philip, D.F. 1987. A Reconnaissance Survey of Lillooet Lake. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Philip, D.F., 1990, A Reconnaissance Survey of Little Lillooet Lake. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Phillips, A.C. and Barraclough, W.E. 1978. Early marine growth of juvenile Pacific salmon in the Strait of Georgia and Saanich Inlet, British Columbia. Fish. Mar. Serv. Tech. Rep. 830, 19 p.

Platts, W.S., R.J. Torquemada, M.L. McHenry, and C.K. Graham. 1989. Changes in salmonid spawning and rearing habitat from increased delivery of fine sediment to the South Fork Salmon River, Idaho. Trans. Am. Fish. Soc. **118**: 274–283.

Polovina, J.J., Howell, E., Kobayashi, D.R., Seki, M.P. 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Prog. Oceanogr. 49: 469-483.

Pon, L.B., Tovey, C.P., Bradford, M.J., MacLellan, S.G., and Hume, J.M.B. 2010. Depth and thermal histories of adult sockeye salmon (*Oncorhynchus nerka*) in Cultus Lake in 2006 and 2007. Can. Tech. Rep. Fish. Aquat. Sci. 2867: iii + 39 p.

Pottinger Gaherty Environmental Consultants Ltd. 1996. Stream Classification of Fish Hatchery Creek and East Fork Corbold Creek, Pitt River Watershed, F.L. A19201, Consultant Report Prepared For J.S. Jones Holdings Ltd., Maple Ridge, B.C. 1996. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Preikshot, D., R.J. Beamish, , and R.M. Sweeting. 2010. Changes in the diet composition of juvenile sockeye salmon in the Strait of Georgia from the 1960s to the early 21st Century. NPAFC Doc. 1285. 17 pp.

Quigley, J.T. and D.J. Harper. 2004. Streambank protection with rip-rap: an evaluation of the effects on fish and fish habitat. Can. Manuscr. Rep. Fish. Aquat. Sci. 2701: xiv + 76 p.

Quigley, J.T., and D.J. Harper. 2005. Compliance with Canada's Fisheries Act: a field audit of habitat compensation projects. Environmental Management 37(3): 336-350.

Quinn, T.P. and B.A. Harter. 1987. Movements of adult sockeye salmon (*Oncorhynchus nerka*) in British Columbia Coastal Waters in relation to temperature and salinity stratification: ultrasonic telemetry results, pp. 61–77 *In* H.D. Smith, L. Margolis and C.C. Wood [eds.], Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 95.

Rensel, J.E., 2007. Fish kills from the harmful alga *Heterosigma akashiwo* in Puget Sound: Recent Blooms and Review. Prepared by Rensel Associates Aquatic Sciences for the National Oceanic and Atmospheric Administration Center for Sponsored Coastal Ocean Research (CSCOR), Washington, DC, 59 pp., http://www.whoi.edu/fileserver.do?id=39383&pt=2&p=29109.

Rensel, J.E., Nicola, H., and T.M. Tynan. 2010. Fraser river sockeye salmon marine survival decline and harmful blooms of *Heterosigma akashiwo*. Harmful Algae 10: 98–115.

Richoux, N.B., C.D. Levings, L. Lu, and G.E. Piercey. 2006. Survey of indigenous, non-indigenous and cryptogenic benthic invertebrates in Burrard Inlet, Vancouver, British Columbia. Canadian Data Report of Fisheries and Aquatic Sciences 1183:20 pp.

Ricker, W.E. 1933. Destruction of sockeye salmon by predatory fishes. Biol Bd. Canada, Pacific Prog. Rept. No. 18, 3-4.

Ricker, W.E., 1976. Review of the rate of growth and mortality of Pacific salmon in salt water and noncatch mortality caused by fishing. J. Fish. Res. Board Can. 33:1483–1524.

Richardson, J.S., T.J. Lissimore, M.C. Healey and T.G. Northcote. 2000. Fish communities of the lower Fraser River (Canada) and a 21 year contrast. Environmental Biology of Fishes 59: 125-140.

Riddell, B. 2004. Pacific salmon resources in central and north coast British Columbia. Vancouver, BC: Pacific Fisheries Resource Conservation Council. 157p.

Robinson, D.G. 1969a. Data record: number, size composition, weight and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia April 24–25, l968. Manuscr. Rep. (FRBC) 1067, 63 p.

Robinson, D.G. 1969b. Data record: number, size composition, weight and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia July 4–6, 1967. Manuscr. Rep. (FRBC) 1012, 71 p.

Robinson, D.G., W.E. Barraclough, and J.D. Fulton. 1968a. Data record: number, size composition, weight and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia May 1–4, 1967. Manuscr. Rep. (FRBC) 964, 105 p.

Robinson, D.G., W.E. Barraclough, and J.D. Fulton. 1968b. Data record : number, size composition, weight and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia June 5-9, 1967. Manuscr. Rep. (FRBC) 972, 109 p.

Roseberg, G.E., and G.L. Greer. 1985. Migration rate and behaviour of sockeye and chum salmon through trained and untrained sections to the lower Fraser River. Can. Tech. Rep. Fish. Aquat. Sci. 1349. 25p.

Rosenau, M. 2000. Fraser River Fish Study – UBC. 2000. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Sanderson, B.L., K.A. Barnas, and A.M. Wargo Rub. 2009. Nonindigenous species of the Pacific Northwest: An overlooked risk to endangered salmon? BioScience 59(3):245-256.

Sastri A.R. and J.F.Dower. 2009. Interannual variability in chitobiase-based production rates of the crustacean zooplankton community in the Strait of Georgia. Marine Ecology Progress Series. 388: 147–157.

Schweigert, J. And J. Cleary. 2010. Small pelagic fishes in the Strait of Georgia. 120p. *In* W.R. Crawford, and J.E. Irvine [eds.], State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/053.

Schweigert J. and V. Haist. 2007. Stock assessment for British Columbia herring in 2006 and forecasts for the potential catch in 2007. Report No. 2007/002, Government of Canada, Fisheries and Oceans Canada, Nanaimo

Schubert, N.D. 1982. A Biophysical Survey of 30 Lower Fraser Valley Streams. Report of Fisheries and Aquatic Sciences. Fisheries and Oceans. New Westminster. 130 pp. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Schubert, N.D and J.A. Tadey 1997. Estimation of the 1994 Birkenhead River Sockeye Salmon (*Oncorhynchus nerka*) Escapement. Can. MS Rep. Fish. Aquat. Sci. 2399: 35p.

Schubert, N.D., Beacham, T.D., Cass, A.J., Cone, T.E., Fanos, B.P., Foy, M., Gable, J.H., Grout, J.A., Hume, J.M.B., Johnson, M., Morton, K.F., Shortreed, K.F., Staley, M.J., and Withler, R.E. 2002. Status of Cultus Lake sockeye salmon (*Oncorhynchus nerka*). Canadian Science Advisory Secretariat Res. Doc. 2002/064.

Schubert, N.D. and Houtman, R. 2007. Estimating the 1998 Fraser River sockeye salmon (*Oncorhynchus nerka*) escapement, with special reference to the effect of migration stress on estimation accuracy. Can. Tech. Rep. Fish. Aquat. Sci. 2732: ix + 121 p.

Shortreed, K.S., Morton, K.F., Malange, K., Hume, J.M.B., Factors Limiting Juvenile Sockeye Production and Enhancement Potential For Selected B.C. Nursery Lakes, Canadian Science Advisory Secretariat, Research Document 2001/098.

St. John, M.A., J.S. MacDonald, P.J. Harrison, R.J. Beamish, and E. Choromanski. 1992. The Fraser River plume: some preliminary observations on the distribution of juvenile salmon, herring, and their prey. Fisheries and Oceanography 1(2):153-162.

Stalberg, H.C., R.B. Lauzier, E.A. MacIsaac, and C. Murray. 2009. Canada's policy for conservation of wild Pacific salmon: Stream, lake and estuarine habitat indicators. Canadian Manuscript Report of Fisheries and Auatic Sciences 2859:135p.

Statistics Canada Censuses. 1986. Canadian Census. http://www.bcstats.gov.bc.ca/census.asp

Statistics Canada Censuses. 1991. Canadian Census. http://www.bcstats.gov.bc.ca/census.asp

Statistics Canada Censuses. 1996. Canadian Census. http://www.bcstats.gov.bc.ca/census.asp

Statistics Canada Censuses. 2006. Canadian Census. http://www.bcstats.gov.bc.ca/census.asp

Statistics Canada. 1986 Canadian Census of Agriculture: British Columbia. Ottawa: Ministry of Supply and Service Canada, 1987. Catalogue number 96-112

Statistics Canada. 1991 Agricultural Profile of British Columbia, Part One. Ottawa: Ministry of Industry, Science, and Technology, 1992. Catalogue number 95-393

Statistics Canada. 1996 Agricultural Profile of British Columbia. Ottawa: Ministry of Industry, 1997. Catalogue number 95-181-XPB

Statistics Canada. 2007. 2006 Census of Agriculture, Farm Data and Farm Operator Data, for British Columbia Census Subdivisions, 2006 and 2001 Agricultural Census Data (table). Catalogue no. 95-629-XWE. Ottawa. May 16 http://www.statcan.gc.ca/pub/95-629-x/2007000/4123856-eng.htm (accessed November 2010).

Statistics Canada. 2008. Shipping in Canada. 2008. published from 2000-2010, Statistics Canada, Ottawa. http://www.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=54-205-X&chropg=1&lang=eng

Stobbart, A. 2006. Upper Pitt River: Streams and fisheries resources. Fisheries and Oceans Canada, Pitt Sockeye Satellite, Dwedny, BC, 10p.

Sweeting, R.M., R.J. Beamish, C.M. Neville, E. Gordon, E. and K. Lange. 2008. Strait of Georgia juvenile salmon: The same in 2007, only different, pp. 102–105 *In* J.R. Irvine and W.R. Crawford [eds.], DFO Can. Sci. Advis. Sec. Res. Doc. 2008/13.

Swiatkiewicz, V. 1975. Untitled Report: Fisheries Data for Cultus Lake. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Thomson, K.A., Ingraham, W.J. Healey, M.C., Leblond, P.H., Groot, C. and Healey, C.G. 1992. The influence of ocean currents on latitude of landfall and migration speed of sockeye salmon returning to the Fraser River. Fish. Oceanogr. 1: 163–179.

Thompson, W.J., Sutherland, T.F., Cook, N.A., and Macdonald, J.S. 2009. Bibliography for environmental assessments associated with port developments at Fraser River Delta and Prince Rupert Harbour, British Columba. Can. Tech. Rep. Fish. Aquat. Sci. 2857: v + 216p.

Tovey, C.P., M.J. Bradford, and L-M. Herborg. 2008. Biological Risk Assessment for Smallmouth bass (*Micropterus dolomieu*) and Largemouth bass (*Micropterus salmoides*) in British Columbia. CSAS Research Document 2008/075.

Trudel, M., S. Tucker, A. Mazumder, D. Mackas, R. Sweeting and I. Perry. 2008. Prey quality and food web interactions in the Strait of Georgia. Annual Report – Research Program, Fisheries and Oceans Canada, Nanaimo, BC, 6p.

Trudel, M., S. Tucker, J. Irvine, K. Hyatt, G. Gillespie, J. Schweigert, and D. Welch. 2010. Hypothesis: Outside of Georgia Strait, oceanographic conditions, food, and/or predators (including squid) are important contributors to the Fraser sockeye situation. Presentation to the PSC Workshop.

Tucker, S., M. Trudel, D.W. Welch, J.R. Candy, J.F.T. Morris, M.E. Thiess, C. Wallace, D.J. Teel, W. Crawford, E.V. Farley Jr., and T.D. Beacham. 2009. Seasonal stock-specific migrations of juvenile sockeye salmon along the west coast of North America: implications for growth. Trans. Am. Fish. Soc. 138: 1458–1480.

Tyler, A.V., C.O. Swanton, and B.C. McIntosh. 2001. Feeding ecology of maturing sockeye salmon (*Oncorhynchus nerka*) in nearshore waters of the Kodiak Archipelago. OCS Study MMS 2001-059. 34p.

Usher, J.B.1986. Personal communication, Fisheries Technician. Ministry of Environment (MOE). Fish and Wildlife Branch, Chilliwack. 1986. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Waldichuk, M. 1957. Physical oceanography of the Strait of Georgia, British Columbia. J. Fish. Res. Bd. Can. 14: 321–486.

Waldichuk M., P. Lambert, and B. Smiley. 1994. Exotic introductions into BC marine waters. pp. 220-223. In Biodiversity in British Columbia, edited by Harding. L., and E. McCullum. Ottawa: Environment Canada.

Webb, R. 1987. Personal Communication, Stream files, Fishery Officer, Fisheries and Oceans Canada, Coquitlam Sub-District. New Westminster. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Webb, D.G. 1991. Effect of predation by juvenile Pacific salmon on marine harpacticoid copepods. I. Comparisons of patterns of copepod mortality with patterns of salmon consumption Mar. Ecol. Prog. Ser.72: 25-36

Welch, D.W., Chigirinsky, A.I., and Ishida, Y. 1995. Upper thermal limits on the oceanic distribution of Pacific salmon (*Oncorhynchus* spp.) in the spring. Can. J. Fish. Aquat. Sci. 52: 489-503.

Welch, D.W., Ishida, Y. and Nagasawa, K. 1998. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. Can. J. Fish. Aquat. Sci. 55: 937-948.

Welch, D.W., Melnychuk, M.C., Rechisky, E.R., Porter, A.D., Jacobs, M.C., Ladouceur, A., McKinley, R.S. and Jackson, G.D. 2009. Freshwater and marine migration and survival of endangered Cultus Lake sockeye salmon (*Oncorhynchus nerka*) smolts using POST, a large-scale acoustic telemetry array. Can. J. Fish. Aquat. Sci. 66: 736–750.

Whately, M.R., 1968a. A Reconnaissance Survey of Green Lake. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Whately, M.R., 1968b. A Reconnaissance Survey of Alta Lake. *In* FISS Fish Distributions point file, British Columbia Ministry of Environment, Date accessed: November 2010, Available at: http://a100.gov.bc.ca/pub/fidq/fissPointsSelect.do.

Whitehouse, T.R., D.E. Boyle, C.D. Levings, J. Newman and J. Black. 1993. Fish distribution within a tidal freshwater marsh in the lower Fraser River. Can. Data Rep. Fish. Aquat. Sci. 917: 49 p.

Whitehouse, T.R. and C.D. Levings, 1989. Surface Trawl Catch Data from the Lower Fraser River at Queens Reach during 1987 and 1988, Can. Data Rep. Fish. Aquat. Sci. 768: 53p.

Wilson, A, P. Slaney, and H. Deal. 2002. Evaluating the Performance of Channel and Fish Habitat Restoration Projects in British Columbia's Watershed Restoration Program. Streamline, B.C.'s Watershed Restoration Technical Bulletin Spring 2002, 3-7p.

Wilson, R.C.H., R.J. Beamish, F. Aitkens, and J. Bell (Eds.). 1994. Review of the Marine Environment and Biota of Strait of Georgia, Puget Sound, and Juan de Fuca Strait. Proc. BC/Washington Symposium on the Marine Environment, January 13-14 1994. Can. Tech. Rep. Fish. Aquat. Sci. 1948. 390p.

Woodey J.C. 1987. In-season management of Fraser River sockeye salmon (*Oncorhynchus nerka*): meeting multiple objectives. Can Spec Publ Fish Aquat Sci. 96:367–374

Xie L. and W.W. Hsieh. 1989. Predicting the return migration routes of the Fraser River sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 46: 1287-1292.

Yin, K., P.J. Harrison and R.J. Beamish. 1997. Effects of a fluctuation in Fraser River discharge on primary production in the central Strait of Georgia, British Columbia, Canada. Can. J. Fish. Aquat. Sci. 54: 1015.1024

Yin, K., Harrison, P.J., Goldblatt, R.H., St. John, M.A. and Beamish, R.J. 1997b. Factors controlling the timing of the spring bloom in the Strait of Georgia estuary, British Columbia, Canada. Canadian Journal of Fisheries and Aquatic Sciences, 54:1985-1995.

Appendix 1 – Statement of Work

**Cohen Commission of Inquiry into the Decline of
Sockeye Salmon in the Fraser River**

"Sockeye Habitat Analysis in the Lower Fraser and the Strait of Georgia"

SW1 Background

1.1 The Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (www.cohencommission.ca) was established to investigate and report on the reasons for the decline and the long term prospects for Fraser River sockeye salmon stocks and to determine whether changes need to be made to fisheries management policies, practices and procedures.

1.2 Information is needed to assess sockeye habitat quality and quantity in the Lower Fraser River and the Strait of Georgia where most Fraser Watershed human development activities are concentrated.

SW2 Objectives

2.1 To describe historical trends in development activities in the Lower Fraser and the Strait of Georgia that impact sockeye habitats.

2.2 To quantify the sockeye habitats that are exposed to human development activities and to determine the severity of impacts from those activities.

2.3 To describe linkages between Fraser sockeye declines and human development activities in the Lower Fraser River and the Strait of Georgia.

SW3 Scope of Work

3.1 Prepare a habitat inventory for sockeye habitats in the Lower River (below Hope) and identify human activities that could affect them.

3.2 Analyze Fraser Estuary development including impacts of larger vessels e.g., oil tankers, proposed expansion of Vancouver Airport Fuel Delivery Project, development of ports, bridges and damage from dredging.

3.3 Describe human activities in the Strait of Georgia and identify those which could negatively affect sockeye salmon. Evaluate Coastal Zone protection strategies related to shoreline development, shipping, aquaculture and oil tanker traffic.

3.4 Provide a synopsis of water quality conditions in the Strait of Georgia along the sockeye migration routes.

3.5 Quantify sockeye food abundance in the Strait of Georgia.

SW4 Deliverables

4.1 The Contractor will organize a Project Inception meeting to be held within 2 weeks of the contract date in the Commission office. The meeting agenda will be set by the Contractor and will include a work plan for project implementation.

4.2 The main deliverables of the contract are 2 reports analyzing sockeye habitat in the Lower Fraser and the Strait of Georgia: 1) a progress report, and 2) a final report. The style for the Reports will be a hybrid between a scientific style and a policy document. An example of a document which follows this format is the BC Pacific Salmon Forum Final Report (www.pacificsalmonforum.ca).

4.3 A Progress Report (maximum 20 pages) will be provided to the Cohen Commission in pdf and Word formats by Nov. 1, 2010. Comments on the Progress Report will be returned to the contractor by Nov. 15, 2010.

4.4 A draft Final Report will be provided to the Cohen Commission in pdf and Word formats by Dec. 15, 2010. The draft Final Report should contain an expanded Executive Summary of 1-2 pages in length as well as a 1-page summary of the "State of the Science". Comments on the draft Final Report will be returned to the contractor by Jan. 15, 2011 with revisions due by Jan. 31, 2011.

4.5 The Contractor will make themself available to Commission Counsel during hearing preparation and may be called as a witness.

4.6 The Contractor will participate in a 2-day scientific workshop on November 30 – December 1, 2010 with the Scientific Advisory Panel and other Contractors preparing Cohen Commission Technical Reports to address cumulative effects and to initiate discussions about the possible causes of the decline and of the 2009 run failure.

4.7 The Contractor will participate in a 2-day meeting presenting to and engaging with the Participants and the public on the results of the LFR/SOG investigations on February 23-24, 2011.

Appendix 2 – Scientific Reviews

Three scientific reviews were provided on the initial rough draft report. The report has been revised and updated to incorporate reviewers comments.

Individual reviews were provided by: (a) Dr. Rick Rouledge, Simon Fraser University, (b) Dr. John Reynolds, Simon Fraser University, and (c) Dr. Marvin Rosenau, BC Institute of Technology.

Comments and responses by the report authors are present in ***italics*** within each review.

Report Title: Fraser River Sockeye Salmon Habitat Analysis: Lower Fraser and Strait of Georgia

Reviewer Name: Rick Routledge

Date: January 3, 2011

1. Identify the strengths and weaknesses of this report.

Major Strengths:

1. Good collection of reference material on the topic;
2. Good attention to the terms of reference;
3. Good quality maps.

Major Weaknesses:

1. Omission of list of references;
2. Inadequate assessment of the quality and completeness of the evidence presented in the references, and lack of specificity in referring to these sources in the text;
3. Imprecision and ambiguity in the text, and inconsistencies within the text and between the text and the maps;
4. Paucity of local, system-specific knowledge;
5. Inadequately justified recommendations;
6. Numerous typographical, grammatical, and other similar sorts of errors.

(Details provided in comments to the authors.)

The author's have addressed the concerns (listed above) found in the preliminary draft report with the revised report enclosed here. The original draft report was submitted early in the process in an incomplete form in order to help facilitate early review comments.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

My major concerns here are that (i) the authors need to provide a more critical assessment of the strengths and weaknesses of the available evidence, and (ii) that they need to be more thorough in describing the potential weaknesses in their approach. In my comments to them below, I have raised a particular concern over the lack of local and system-specific knowledge that underlies their methodology. Although it was not reasonable to ask them to undertake such an extensive task in such a limited time frame, I feel that it is important that the limitations of the approach that they were constrained to take be stated clearly.

The author's have addressed the concern above through the addition and use of an effect assessment method to review potential interactions between human activities and *sockeye habitat use. Limitations in the data as a result of the constraints noted above have been reflected in the report and in the rigour with which conclusions could (or could not) be reached.*

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

Since there seems to be too little time for further analyses of much substance, I would like to propose something more feasible. I suggest that there be more focus in the text on a few key questions that address the heart of the concern. Perhaps this could best be achieved through a more focussed and tersely written Executive Summary (substantial portions of which I noted were copied directly from the main text). For what they are worth, here are my suggestions:

1. To what extent could habitat conditions in the Lower Fraser River and Strait of Georgia explain the decline in Fraser River sockeye returns? (I believe that the authors would agree that Lower Fraser habitat has likely had little impact, and that, by contrast, they would be less definitive in their assessment of the potential impact of the Strait.
2. What can we learn from the relatively strong performance of the Harrison, river-type sockeye? And in the context of this report, what do we know and not know about their use of the habitats in the river, estuary, plume and strait, and about their exit route?
3. What role do these habitats play in the conservation of biodiversity, with special reference to Cultus Lake, Harrison River, Widgeon Creek, Alouette Lake, and Coquitlam Lake sockeye? (I have a sense that the terms of reference unintentionally steered the authors away from the biodiversity issue. Nonetheless, it seems crucial given the COSEWIC status for Cultus Lake sockeye, the emerging importance of Harrison river-type sockeye, and the apparently tenuous viability of the remaining three.

These are constructive suggestions. The author's have been cognizant of the potential interactions and outcomes related to sockeye production throughout the revised text.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

Unfortunately, though the recommendations have merit in my estimation, they did not seem to flow naturally from the authors' assessment of the available evidence. Furthermore, I sense that the authors were unduly constrained in considering recommendations for habitat management solely in the context of sockeye salmon. For example, gravel extraction and damage to side channels, sloughs and wetlands are potentially of far greater consequence to more broadly based conservation concerns including other salmon species. Although this is not the venue for a thorough investigation of these tangential issues, I believe that it is important for us all to maintain a broader perspective on the value of such habitats, and to seize whatever opportunities are available to promote their protection. To that end, I suggest that, in terms of this report, they include further commentary on (i) the emerging importance of river-type sockeye salmon in the Harrison (and potentially elsewhere), (ii) the importance of maintaining biodiversity to deal with such fluctuating contingencies, (iii) the relatively extensive reliance of these fish on Lower Fraser habitat (with a careful assessment of how much is truly known about this), (iv) the importance of this habitat more generally, and then (v) recommendations for its preservation.

Also, I found no mention in the report of Alouette or Coquitlam Lake sockeye salmon. In the biodiversity context, It is important that these not be forgotten. They are also highly valuable success stories that can add considerable impetus to recommendations for habitat conservation and restoration. I strongly recommend that these be included in the text with appropriate recommendations for the continuation of such initiatives.

I believe also that there has been speculation that the rapid reestablishment of sea-run sockeye salmon in Alouette Lake may also be attributable to a river-spawning population that strayed back up into the lake. River-type sockeye have also been hypothesized, in my understanding, as a potential explanation for similar successes in other lakes such as Quesnel Lake in the Fraser watershed and Redfish Lake in the Columbia watershed. If so, this provides further justification for paying careful attention to river-type sockeye salmon populations.

Finally, there remains much goodwill toward salmon conservation. In the densely populated Lower Fraser area, the large and aging population base provides a substantial potential volunteer workforce. There is also a substantial base of organizations dedicated to preserving salmon habitat with considerable local knowledge. Though it is likely not feasible for the authors to consult with these people, I would encourage them to recognize their knowledge, commitment, and achievements, and to recommend that their work not only continue to be supported, but that their role be extended where feasible.

The author's have attempted to address these ideas and concerns in the revised report.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

I'd recommend focussing effort on gaining further understanding of the rearing and seaward migration of Harrison sockeye, recognizing, though, that this would likely become increasingly difficult as the fish moved further from their spawning area and began to mix with other species. Presumably these fish are far too small at that stage for acoustic tagging, and it would be very difficult to track their movements through areas that potentially contained much more abundant fish from other populations.

In addition, it could be valuable to focus more attention on other river-type sockeye populations, of which several have been identified. Widgeon Creek is an obvious example, and, though I'm not an expert, I suspect that there will be others in the Lower Mainland as well as elsewhere. A comparison of trends in their escapement numbers could be revealing. This could well be a valuable project for development in collaboration with local volunteers.

Also, though I remain regrettably unclear as to the current state of knowledge regarding conditions in the Strait of Georgia and their impact on the juvenile migrants, this seems to me to be of potentially critical importance. I use the word, "potentially" here in that what I've seen of the acoustic tagging results suggests that the young sockeye migrate through there very quickly. I look forward to a more detailed appraisal of the evidence regarding the juvenile migrants through this area in a revised report from the authors. Also, in light of this potentially fast migration and other evidence, I would most definitely extend the geographic area for this concern further out along the migration route – at least as far as Queen Charlotte Sound. I would encourage the authors not to feel too constrained by the limits in their mandate to make such recommendations. I hope that this topic will also emerge from both the report on the marine environment and the report on aquaculture impacts, and that it will also be considered in the overview report on cumulative impacts.

The author's agreed. We have augmented to the text and results to strengthen this area of discussion.

6. Please provide any specific comments for the authors.

The authors appear to have done a thorough job of identifying a substantial body of reference material and of summarizing the reported findings contained therein. Nonetheless, I found the report to be lacking in several key areas. I summarize these as follows:

1. The authors have paid insufficient attention to the quality of the evidence that they have pulled together. At times, this is critically important. For example, much may be learned through a careful examination of the rearing and migration biology of the river-type sockeye salmon that spawn in the Harrison River whose 2009 returns were remarkably strong in comparison to other populations in the Fraser watershed. The report cites three references to support their conclusions regarding rearing habitat, use of the Fraser estuary and near-shore marine area, and subsequent marine migration routes. Some of the supporting information is remarkably weak, consisting, e.g., of a few sampled fish caught off the west coast of Vancouver Island in one sampling season only. The authors need to probe for such weaknesses and provide a more careful assessment of the basis for the conclusions that they draw.
2. The authors conclude that the sojourn time and migration route of juvenile sockeye salmon in the Strait of Georgia depend on food availability and such physical conditions as salinity and temperature. They also produce interesting and potentially valuable maps. However, the methodology leading to these maps is inadequately explained. Furthermore, they do not appear to have investigated the potential for any time trends in these phenomena that might explain the decline in Fraser River sockeye returns leading up to 2009. (I am also not confident that their assertion regarding the importance of copepods in the diet of juvenile Fraser sockeye salmon is accurate.)
3. I note that the list of references is yet to be provided. This would help the reader considerably, but the document will still be very difficult to assess. It is not adequate for conclusions to be stated on the basis of reference material that is cited only through a lengthy list of references on a set of maps. For the reader to assess the strength of the arguments leading to the authors' conclusions, he or she needs to be provided with appropriate, individually referenced statements.
4. Much of the text is ambiguous and imprecise, and at times, appears to be inconsistent

with the maps. For example, the authors state in the text that the lower reaches of the river are not used extensively for juvenile rearing and that the juveniles migrate through the lower reaches and estuary quickly. Yet the map marks this stretch of the river in red, indicating that it is very important habitat.

5. The recommendations, though potentially valuable, are inadequately justified. For example, the authors recommend tightened regulations on aspects of habitat management such as dredging that they state earlier have no identifiable influence on Fraser sockeye salmon.
6. I am also concerned over the lack of local, system-specific knowledge that went into this report, though perhaps this is more a reflection of the general erosion of our collective knowledge base than anything else. I cite the Pitt River system as an example. The authors attempted to assess the role of such human alterations as logging activity by statistical analyses of centrally stored data. While this is a useful endeavour, there are other local events that the approach seems not to capture. In this case, these include log accumulations at the upper end of Pitt Lake and the rerouting of the primary current through the upper portion of Widgeon Slough to a more easterly channel for several years. The latter event in particular could have had a substantial impact on the small sockeye salmon population in the slough. It may also have been caused indirectly by logging activity, but with a considerable time lag that was not presumably considered in the statistical analyses.
7. The text needs a thorough copy editing. It contains numerous typographical and grammatical errors.

The author's have attempted to address the concerns listed above and revised and augmented the attached report where possible. In some instances (use of local knowledge) the scope of the review and time available to conduct the review were not sufficient to address all the concerns raised above.

Report Title: Fraser River Sockeye Salmon Habitat Analysis: Lower Fraser and Strait of Georgia

Reviewer Name: John Reynolds

Date: 13 January 2011

1. Identify the strengths and weaknesses of this report.
This report is reasonably comprehensive, especially given the tight timeline. The maps are a real strength, packed with information and readily understandable, though the print is readable only after zooming in on the electronic version. A weakness is lack of detail in some sections, including any indication of uncertainty in the information, as outlined in my detailed report below. My review is hampered by the fact that the draft that was sent lacks references. This makes it difficult to evaluate the evidence for many of the assertions. *The author's have revised and augmented the enclosed report to reflect the reviewers concerns.*
2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?
The interpretations seem fine. I did not notice any tables of data, which would be helpful as Appendices to enable analyses. Overall, this preliminary draft seems to be on the right track.
3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?
I did not notice any statistical analyses. Instead, the report relies on visual representations of data through the many graphs and maps. I would have liked to see statistical analyses of area-specific changes in habitat quality versus area-specific changes in sockeye productivity. *This is a valid issue, the author's have more fully addressed the potential interactions and outcomes related to sockeye production throughout the revised text. The author's have addressed the concern above through the addition and use of an effect assessment method to review potential interactions between human activities and sockeye habitat use.*
4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?
Yes, especially given that many of the indicators of human activity have not worsened over the period of 1990-2010, whereas sockeye aggregate stock productivity has been declining since

about 1992.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

Long-term monitoring of habitat quality, based on a statistically defensible and biologically meaningful design.

6. Please provide any specific comments for the authors.

See below (comments).

Review of Fraser River Sockeye Salmon Habitat Analysis: Lower Fraser and Strait of Georgia

John D. Reynolds

Earth to Ocean Research Group, Department of Biological Sciences, Simon Fraser University

This preliminary draft has some incomplete sections and no references, so my review needs to be considered in that light. I feel that this is on track to be a solid report, assembling a large amount of information in the time available. The graphics in the maps are excellent.

This draft needs a good proof-reading for missing words and so-on. Citations do not appear in the text until Section 2 on habitat use by sub-basins. I hope that the final draft will use authors' names and years rather than numbers, so we can tell easily which papers these are.

Fig. 1. The resolution in the legend is too small for me to be able to read it, even when zoomed in.

The Executive Summary takes up one-third of the report. It is so long relative to the rest of the report that part-way through I was concerned that I was into the main body of the text, with very little detail. If the report is going to retain these proportions, it would help to have some sort of header that helps readers know where they are. To be fair to the authors, a great deal of text appears with the maps, so in terms of content the balance is better, but I'd still suggest reducing the Executive Summary.

The paper mentions pulp mill effluents, but does not mention sewage treatment effluents. Arguably, both may be outside the scope of the terms of reference since pollution is the subject of a separate report. But if one is mentioned, the other should be too.

It would be good to mention that predators, such as pinnipeds, are the subject of a different report. I have forgotten which report is covering non-mammalian predators, such as hake and Humboldt squid, but the Commission should make sure these are tackled somewhere. Also, this report has some information on plankton but does not discuss food per se. This is critical for the Commission to consider. If this is not the report that should have covered it, then a cross-reference should be provided to the report that does.

In terms of recommendations, what about programs to re-connect lost off-channel habitats, create more natural floodplains by moving dikes, and so-on?

p. 3. The six objectives do not map directly onto the ones described in the Scope of Work, but they are probably close enough.

The habitat use maps (3 A-D) are very impressive. They summarize a lot of information with literature citations in a very clear manner (if readers zoom in enough to read them).

p. 8. Habitat use and movements by Harrison sockeye are very important, because this population has been bucking the trend of decline by other stocks. So we really need as much detail in this section as possible, including not only literature citations but also an indication of uncertainties or conflicting or patchy information. For example, do we really know for sure that no Harrison River sockeye migrate out through the top of Georgia Strait? I understand that DFO surveys have found the fish off the west coast of Vancouver Island, but more information about the evidence for how they get there would be helpful. Are the DFO surveys on both sides of Vancouver Island clear about this? Is there agreement about the data in the two surveys and their interpretation? This section needs both more detail and critical appraisal of the evidence.

I did not see any mention of Cultus Lake predators or changes in lake quality, including an explanation of why the salmon are not using most of the beaches anymore. This is important because the Commission has already heard views expressed that even if the mixed-stock fishery issue were fixed, the lake's carrying capacity will not support a rebound of this stock. Not everyone agrees. This technical report should provide the critical evidence on this.

p. 9. I will send a detailed report by DFO biologist Al Stobbart that will be useful for information about Upper Pitt Lake spawning tributaries.

p. 10 bottom. We really need references and lots of detail about the surveys that are referred to concerning Harrison sockeye habitat use.

p. 11. It would be nice to see the figures on proportions of fish that use the northern or southern routes past Vancouver Island.

p. 12. With one exception, the list of human indicators of development looks quite reasonable given the time available, and the accompanying maps are packed with useful data and good explanations. The exception concerns river gravel mining. This is a huge issue in the mainstem of the Fraser, especially in the “Gravel Reach”, and it seems like an odd omission from this list. While most of this activity occurs outside the window when sockeye are in the river, that is true for dredging too, yet that topic is discussed.

p. 16. The discussion of contaminants and water quality, which includes two maps, should be cross-referenced to the Commission’s report that deals specifically with that subject.

Map 14: Non-indigenous species. The increase in the total number of species is striking, but so is the apparent stability of the number of non-native freshwater fishes since 1930. I cannot think of another case where non-native species have not increased in the past 50 years. I doubt that this is real, and worry that it’s an artifact of lack of new information.

p. 23. I hope the Commission takes note of the case for a more unified vision and integrated approach in management. The final report of the BC Pacific Salmon Forum (Hon. John Fraser, Chair) made a similar recommendation, with a particular emphasis on watershed governance. It would be worth mentioning that with reports like that, implementation of such a vision would not need to start from scratch.

The federal Species at Risk Act is mentioned only twice in passing. Is it politically incorrect to suggest that the federal government might want to consider protecting wild salmon and their habitats under this Act? The Committee on the Status of Endangered Species (COSEWIC) has recommended a few wild salmon populations for protection, but these have been turned down.

There is currently discussion of the potential for creating a provincial endangered species act. It would be interesting to consider whether this might be helpful in protecting salmon and their habitats.

Report Title: Fraser River Sockeye Salmon Analysis—Lower Fraser and Strait of Georgia.

Reviewer Name: Marvin Rosenau

Date: 22 Dec 2010

1. Identify the strengths and weaknesses of this report.

The primary strength of the report is the comprehensiveness of the issues. The primary weakness of this report is that because the authors covered so many topics, and over such a wide geographic area, they are dealt with in a relatively superficial way. There are very little in the way of data that could be considered an analysis of possible cause and effect of the sockeye collapses—lots of speculation that things didn't have an impact, but not a lot of hard-core numerical analysis. Further, some of the things that may have happened earlier on, say in the 1970's or 1980s, and had a lag effect (say, the large-scale sand removal in the lower river, forest harvest in the 1970s and 80's, which may have not impacted the spawning streams for two decades) are not dealt with because the things that they really looked at were from c.a., 1990 and onwards. Now to be totally fair, I think that the task that the consultant's were given was so large that it was impossible for them to do justice to the subject given the time frame and the resources available. And, to do a proper reporting of the issues under this subject umbrella, the paper should clearly state this.

The reviewer has provided valuable input and comments. Where possible, the author's have revised and addressed the comments in the final draft. The reviewer's comments are appreciated.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

Again, I would say that the data are not particularly dealt with in depth. As an example, the questions surrounding new chemicals/hormone mimics in the wastewater treatment plants since 1990 is given relatively short shrift. And the changes in water quality in the SOG show some trends that are very different from 1990, but little analysis or examination of the potential for cause and effect was undertaken. Again, to be fair, it is unlikely that the reporters had the resources to do these subjects justice, but the report should state this.

The author's have attempted to augment their report to provide some additional input to these issues.

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

I think the main potential issues were covered; having said that much of the analysis was not particularly quantitative (correlation, PCA, multiple regression) and for many of the issues the statement was: "Things are getting better (e.g., wastewater treatment), so we can't ascribe any declines in sockeye to this issue." While the resources to do such comprehensive analyses are certainly very large, I still think that the writers should have emphasized the links with sockeye much more clearly.

The author's have addressed the concern above through the addition and use of an effect assessment method to review potential interactions between human activities and sockeye habitat use.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

There is a lot of editorial cleanup to do. Much of the material in the EXSUM is repeated again in the text and the EXSUM should be considerably condensed, in my view. The authors should really stick to the impacts that might have realistically affected sockeye, and leave out stuff that is superfluous.

The comments are appreciated. The report has been updated, sections that were not yet written in the draft have been written and reviewed.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

Fish distributions and abundances for particular issues in the LM that might have influence on Fraser sockeye. For stream-rearing sockeye, there is a large effort needed in the lower mainland, particularly since Harrison Rapids fish have exploded in numbers. I would suggest that the migration routes/timing in SOG are also important as other parts of the sockeye issue suggest that it is early marine rearing that is where the mortality is likely occurring.

There is likely quite a bit of plankton and water quality information in the SOG that either needs to be collected, or material that has already been obtained, properly analyzed. However, this is outside of my sphere of experience, and I make this recommendation with some qualification.

The author's have revised the report where possible with available information.

6. Please provide any specific comments for the authors.

Comments are provided in an attached appendix to these review pages. They are comprehensive and detailed.

I am not sure why the citations are numbered in the text, sometimes, and then named in other parts. The numbering system is confusing.

I am not sure why some of the citations in the list of references have yellow highlights. This should be dealt with at some point, in my view.

The comments are appreciated. The final draft report has been revised to reflect the input.

Appendix 3 – Detailed observations of Sockeye Distribution and Habitats Use in the lower Fraser Watersheds, lower Fraser River and Strait of Georgia

Detailed observations for sockeye distribution and habitat use were compiled for the following locations and life history stages including:

- Harrison Lake and Lillooet – Spawning habitats (adult spawning and egg incubation);
- Harrison Lake and Lillooet – Rearing habitats (juvenile rearing and smolt migration);
- Chilliwack and Cultus Lake – Spawning habitats (adult spawning and egg incubation);
- Chilliwack and Cultus Lake – Rearing habitats (juvenile rearing and smolt migration);
- Pitt Lake – Spawning habitats (adult spawning and egg incubation);
- Pitt Lake – Rearing habitats (juvenile rearing and smolt migration);
- Lower Fraser River – Rearing (juvenile) and Migration (smolt and adult); and
- Strait of Georgia - Rearing (juvenile) and Migration (smolt and adult).

Harrison Lake and Lillooet – Spawning Habitats

The majority of sockeye spawning activity and spawner abundance in the Harrison River watershed is located in Weaver Creek, a tributary to Harrison River located south of Harrison Lake (Marshall and Hancock 1985, Shortreed et.al. 2001, Schubert and Houtman 2007, Pearson and Chiavaroli 2010, Holtby and Ciruna 2007, Labelle 2009) (Map 3- B-ii). A lower proportion of spawning habitats are located in the Harrison Lake tributaries including Trout Lake Creek, Big Silver Creek, Douglas Creek (Marshall and Hancock 1985, Marshall and Hancock 1985, Schubert 1982, Pearson and Chiavaroli 2010) and the Harrison River rapids downstream of the lake and in several other Harrison Lake tributaries including: Sloquet Creek, Tipella Creek, Mystery Creek, and Coburg Creek (BIOTERRA Consulting Ltd. 1998a, BIOTERRA Consulting Ltd. 1998b, Marshall and Hancock 1985, Lewis 1994, Marshall and Hancock 1985, Pearson and Chiavaroli 2010). A small number of spawners are observed in the Chehalis River (Lewis 1994, Pearson and Chiavaroli 2010). Harrison sockeye are considered a late-run stock with spawning generally occurring between August and late October (Schubert and Houtman 2007, Labelle 2009).

The Lillooet sub-basin is upstream of Harrison Lake (Map 3-A-i). Lillooet Lake and Little Lillooet Lake and its tributaries flow downstream through the Lillooet River into Harrison Lake. Major spawning areas in the Lillooet watershed include the Birkenhead River, and to a lesser extent, the Upper Lillooet River, lower Green River, and John Sandy Creek (Brown et.al. 1979, Marshall et.al. 1979, MELP 1996, Shortreed et.al. 2001, Schubert and Tadey 1997, Houtman et.al. 2000, Schubert and Houtman 2007). Additional spawning areas are located in Billy Goat Creek (Brown et.al.

1979). Lillooet sockeye are considered a late-run stock with spawning generally occurring between August and late October (Schubert and Houtman 2007).

Harrison Lake and Lillooet Lake – Rearing Habitats

Spawning sockeye deposit their eggs in redds created as shallow depressions or pockets dug gravel substrates. The incubation period for sockeye eggs is variable and directly associated by water temperature days accumulated over the incubation period (Brannon 1987, Burgner 1991). Free-swimming young fry emerge from redds and migrate quickly to lake rearing areas. The mean time interval from spawned eggs to peak emergence of fry was observed to be 173 days for Weaver Creek sockeye (Foerster 1968, Burgner 1991) (Map 3-B-i).

Emergent fry typically migrate downstream during low light conditions and night-time, and in the quick surface waters of the river (Foerster 1968, Burgner 1991). No observations readily exist for Harrison Lake sockeye, but it is expected to be the likely behavioural strategy used by majority of emergent sockeye fry spawning tributaries. Weaver Creek fry migration is more complex and includes downstream migration at night through Morris Slough, downstream migration in Harrison River for approximately 1 kilometre, followed by a reorientation and upstream migration into Harrison Lake (Shortreed et.al. 2001, Burgner 1991). Birkenhead fry migrate downstream to Lillooet Lake to rear for one year prior to migrating to the ocean (Map 3-A-i). A variable proportion of fry from the Lillooet Lake migrate further downstream to rear in Harrison Lake (Shortreed et.al. 2001).

Most of the Harrison watershed sockeye rear in the lake for one year prior to migrating to the ocean. However, fry emerging from spawning grounds in the Harrison River rapids are not able to move upstream past the rapids and into the lake. These fry are considered river-type sockeye (Holtby and Ciruna 2007) and migrate downstream in April and May and rear in the lower Fraser off channel and backwater channel habitat areas over the early summer (Birtwell et.al. 1987, Beamish et.al. 2003, Burgner 1991). Small numbers of sockeye fry are found throughout many non tidal portions of the lower Fraser River and are considered to be Harrison Rapids 0+ river-type sockeye.

Juvenile sockeye in Harrison Lake are pelagic planktivores feeding on the water column zooplankton (i.e., Henderson et al 1991). Lake rearing sockeye show a distinct vertical migration and feeding behaviour used to optimize foraging, predator avoidance, and metabolic efficiency (Clark and Levy 1988, Levy 1990, Levy et.al. 1991). Sockeye fry rearing in Harrison Lake are substantially larger than those found in many other nursery lakes in BC (Shortreed et.al. 2001, Pearson and Chiavaroli 2010). Harrison and Lillooet sockeye aged 1+ migrate as smolts downstream and out to the ocean in April and May.

Harrison river-type fry migrate downstream in the Fraser River in April and May, rear in the Lower Fraser off channel and backwater channel habitats over the early summer (Birtwell et.al. 1987). These 0+ fry enter the Strait of Gerogia at the end of July, having spent as much as 5 months in Lower Fraser off channel habitats (Birtwell et.al. 1987, Beamish et.al. 2003, Burgner 1991). Harrison 0+ sockeye remain in the Strait of Georgia for several months prior along the south western area of the Strait of Georgia and leave the strait through the Juan de Fuca Strait (Beamish et.al. 2003) and are found off the west coast of Vancouver Island in February and March (Tucker et.al. 2009).

Chilliwack and Cultus Lake – Spawning Habitats

The Chilliwack watershed sockeye consists of two sockeye salmon stocks; Cultus Lake and Chilliwack Lake (Map 3-B-ii). Cultus Lake sockeye are a lake beach spawning stock where spawning habitats are found on Lindell Beach at the southwest end of the lake (Swiatkiewicz 1975, DFO 2002, Schubert et.al. 2002, DFO 2010). Historically, spawning habitats were also located along the lake foreshore at Snag Point, Spring Hole, and Mallard Bay, as well as in Sweltzer and Spring creeks (Schubert et.al. 2002). Chilliwack Lake sockeye spawn in the Chilliwack River upstream of Chilliwack Lake and in Foley Creek a tributary of Chilliwack River downstream of Chilliwack Lake (Buxton 1995, Fedorenko 1984, MELP 1995a, MOE 1986, and Schubert and Houtman 2007).

Chilliwack Lake sockeye are an early summer spawning run stock whereas Cultus Lake sockeye have historically been considered a late-run stock (Schubert and Houtman 2007). Cultus Lake adult sockeye migrate through Sweltzer Creek and into the lake usually in late September, where they hold for up to two months before spawning (Schubert et.al. 2002, Pon et al. 2010). Peak spawning occurs in late October to early November and is usually complete by mid-December (Schubert et.al. 2002, DFO 2010). However, a shift to an earlier migration period has been documented since 1996, with fish arriving in the lake almost two months earlier than the historic average (Schubert et.al. 2002, DFO 2010). Cultus Lake sockeye is one of three salmon populations that were designated as endangered by the Committee on the Status of Endangered Wildlife in Canada. Recovery actions have been implemented by DFO since 2000.

Chilliwack and Cultus Lake - Rearing Habitats

Sockeye fry in Cultus Lake school and move offshore into deeper water immediately after emergence, with most of the population located in offshore limnetic habitats in early May (Mueller and Enzenhofer 1991, Mueller et.al. 1991, Schubert et.al. 2002) (Map 3-B-i). This offshore behaviour is considered unusual and is speculated to be an adaptation to dense predator populations in the Cultus Lake (Ricker 1933, Schubert et.al. 2002). Literature documenting movement of Chilliwack Lake fry was not found. Juvenile sockeye in the Chilliwack watershed rear in their nursery lake for one year prior to migrating out to the ocean starting in March, peaking at the end of April, and complete by June (Schubert et.al. 2002).

Pitt Lake – Spawning Habitats

Major spawning grounds in the Pitt River watershed are found in the lower 17 km of the Pitt River mainstem upstream of Pitt Lake, and in several main tributaries within this stretch of river: Corbold Creek, Slough Creek, Homer (or Cypress) Creek, Boise Creek, Peter's Slough, and Fish Hatchery Creek (Henderson et.al. 1991, IPSFC. 1972, MELP 1995b, Pottinger Gaherty 1996, Schubert 1982, Schubert and Houtman 2007, Stobbard 2007, and Webb 1987) (Map 3-B-ii). Stobbard (2007) observed as high as 50,000 spawners in the Upper Pitt River mainstem, with the next highest contribution to spawning occurring in Corbold Creek with as high as 30,000 spawners observed. Lower spawning activity has been documented in several other tributaries to the Upper Pitt River including Steve Creek, Pinecone Creek, Trumpeter Creek, Forestry Creek, and Olsen Creek (Stobbard 2007). Additional spawning grounds are found in the Widgeon Creek and slough areas and comprise a small proportion of the total Pitt River sockeye salmon stock (Duval 1975b, Henderson et.al. 1991, MSRM 1984, Schubert 1982, and Schubert and Houtman 2007). Widgeon Slough and Widgeon Slough flow into Pitt Lake near the south end of the lake on its western shore.

Adult sockeye spawners are found in commercial fishing areas adjacent to the Fraser River throughout July and begin arriving at the Pitt River spawning grounds in the middle of August, with peak spawning activity occurring in early to mid-September (Henderson et.al. 1991, Schubert and Houtman 2007). Widgeon Creek and Widgeon Slough spawners arrive later with peak spawning activity between mid-October and the end of November (Henderson et.al. 1991).

Pitt Lake – Rearing Habitats

Fry rearing in Pitt Lake have been observed in nearshore littoral areas in the spring and early summer and move offshore with onset of warmer summer temperatures (Henderson et al. 1991, Mueller and Enzenhofer 1991, Mueller et.al. 1991, Diewert and Henderson 1992).

The mean time interval from spawned eggs to peak emergence of fry was found to be 223 days for Upper Pitt River sockeye (Burgner 1991). Fry production in the Pitt watershed is a result of natural spawning primarily in the Upper Pitt River and supplementary stocking from the Corbold Creek hatchery, which has occurred since the 1960s (Hendersen et. al. 1991, Stobbard 2007). Rearing fry initially school in the north end of Pitt Lake (Henderson et.al. 1991) and move in early summer to the south end of the lake in nearshore littoral areas (Henderson et.al. 1991, Mueller and Enzenhofer 1991, Mueller et.al. 1991, Diewert and Henderson 1992) (Map 3-B-i). By mid to late July, fry in Pitt Lake move offshore toward the centre of the lake (Henderson et.al. 1991). Juvenile sockeye rearing in Pitt Lake exhibit regular diel vertical migration patterns (Diewert and Henderson 1992).

In July surveys, juvenile sockeye were found to move from a depth of up to 50 m during the day to a mean depth of 5 m at night (Henderson et.al. 1991).

Catch data indicate that a small proportion on Pitt Lake fry behave like river-type fry, and migrate out of the lake earlier than the larger proportion of sockeye fry (Henderson et.al. 1991, Mueller and Enzenhofer 1991, Mueller et.al. 1991). Sockeye fry were captured in the lower Pitt River from March to June (Diewert and Hendersen 1992). These fry may have a similar life history strategy to Harrison Lake 0+ fry and rear in off and backwater channel habitats of the Lower Fraser for several months prior to moving into the Strait of Georgia. Based on scale analyses of growth, no evidence has been found to suggest that fry emigrants to the ocean contribute significantly to the Upper Pitt River spawning population (Henderson et.al. 1991). A higher proportion of the juvenile sockeye likely rear in the lake for a year prior to migrating to the ocean (Diewert and Henderson 1992).

No documentation of the migrations of Widgeon Creek and Widgeon Slough fry was found, and therefore it is unclear whether these fry migrate upstream to rear in the lake, remain in the slough or Lower Pitt River, or migrate downstream to the Fraser River.

Lower Fraser River - Rearing and Migration Habitats

The lower Fraser River is primarily used as a migration corridor for all upstream and lower Fraser River sockeye stocks as passage to and from the ocean (juvenile sockeye - Groot and Cooke 1987, Crittenden 1994, Peterman et al. 1994; adult sockeye – Gilhousen 1960, Hamilton 1985, Groot and Quinn 1987, Quinn and Harter 1987, Blackbourn 1987, Woodey 1987, Xie and Hseih 1989,Pascual and Quinn 1991, McDonald 2000, English et al. 2004, Crossin et al. 2004, 2007, Cooke et al. 2008).

Sockeye smolts leave is pulses of millions of fish in loose aggregations (Crittenden 1994) which form into large compact schools with entry into the ocean through the Fraser estuary (Groot 1982, Groot and Cooke 1987). Smolts use the thalweg of the Fraser River, Fraser estuary and concentrated areas of river flow and higher velocity to migrate through the lower river at rates in excess of 20 kilometres per day (Groot and Cooke 1987, Crittenden 1994, Peterman et al. 1994, Welch et.al 2009, Whitehouse and Levings 1989). Catch data from trawl sampling conducted by Whitehouse and Levings (1989) in Queens Reach of the Lower Fraser River near the Port Mann Bridge shows that large numbers of sockeye smolts were captured in bursts and predominantly in off-shore, mid-channel portions of the river indicating that smolts are aggregating and using the river thalweg during migration. Migrating sockeye smolts (aged 1+) are not often caught in seine sampling in the littoral or backwater edges of the lower Fraser River (Whitehouse et al. 1993, Richardson et.al. 2000, Roseneau 2000). Sockeye, like many of the other salmon species, use the higher levels of turbidity in the lower Fraser River as protection against predation as they enter into the ocean (St. John et al. 1992, Gregory and Levings 1996, Gregory and Levings 1998).

Underyearling sockeye fry are found in off channels, backwater habitats and lower river tidal channels of the North arm and Main Arm of the Lower Fraser River and estuary (Birtwell et.al. 1987, Brown et.al. 1989, Dunford 1975, Levings and Nishimura 1997, Levy et.al. 1979, Levy and Northcote 1982). Some juvenile sockeye have also been documented in slow and backwater habitats of the lower Fraser River mainstem further upstream in the Chilliwack / Mission area upstream of the tidal area (Gregory et.al. 1993, Quigley and Harper 2004, Richardson et.al. 2000, Roseneau 2000) and in sloughs in this area including Maria Slough, Camp Slough and Nicomen Slough (Clarke 1982, Herunter et.al. 1989, Lario 1986, and Marshall and Hancock 1985). A few observations of underyearling sockeye fry have been documented in lower reaches of tributaries to the Fraser River (Levings and Nishimura 1997) including Hanna Creek (Elvidge 1986) and Centre Creek and its tributaries within Surrey Bend Park (Whitehouse et al. 1993). Catch data from trawl sampling conducted by Whitehouse and Levings (1989) in Queens Reach of the Lower Fraser River near the Port Mann Bridge indicates that sockeye fry are migrating through the Lower Fraser River in small numbers and in a more even and drawn out migration timing. Catches and density estimates often indicate and wide distribution of sockeye fry and low levels of aggregation at low densities in off and back-channel habitat consistent with use by 0+ river-type sockeye as rearing habitats, rather than sockeye smolts from the majority of the Fraser stocks. These sockeye are thought to be 0+ river-type sockeye from Harrison rapids and are not considered the bulk of the Fraser sockeye smolt migrants. Few yearling sockeye were observed rearing in the lower river and Roberts Banks area (Levings 1985, i.e. Webb 1991), unlike observed distribution and habitat use for Chinook and chum salmon fry (i.e., Levings 1994).

Adult sockeye use two alternative migration routes through the Strait of Georgia including a southern route through Juan De Fuca Strait with holding areas above the southern Gulf Islands and Fraser plume and estuary, and a second northern diversion route through Johnstone Strait and Discovery Passage along an western route in the Strait of Georgia to holding areas in the Fraser plume and estuary (Map 3-D) (Gilhousen 1960, Hamilton 1985, Groot and Cooke 1987, Blackbourn 1987, Groot and Quinn 1987, Woodey 1987, Thomson et al. 1992, English et al. 2004, Crossin et al. 2004, Hinch et al. 2005). Migration residence periods for an individual migrating adult are often less than 1 month (40 km/ day) (Quinn and Harter 1987) in the Strait of Georgia and lower Fraser River dependent on ocean currents (Thomson et al. 1992) during June to September of each year (Hamilton 1985, Woodey 1987). The lower Fraser River is primarily used as a migration corridor for all upstream and lower Fraser River sockeye stocks as passage from the ocean to natal streams of origin.

Strait of Georgia - Rearing and Migration Habitats

With entry into the Strait of Georgia from the Lower Fraser River, sockeye smolts rapidly transition off-shore to clearer, more saline waters of the Strait of Georgia beyond the area of turbidity originating from the Fraser River discharge and plume (Barraclough 1967a, b, c, Barraclough and

Fulton 1967, Robinson 1968a,b, 1969a, b, LeBrasseur et al. 1969, Barraclough and Phillips 1978). Barraclough and Phillips (1978) found sockeye smolts transition more rapidly to the ocean environment than any of the other species of salmon. Smolts moved quickly out into the Strait of Georgia (Barraclough and Phillips 1978). It was also noted that migration across the Strait could be very rapid for salmon smolts depending on Fraser River discharge, prevailing winds and surface current, and take as little as a matter of hours to cross the Strait.

Grout and Cooke (1987) sampled throughout the Strait of Georgia and, based on catch results, proposed two major migration routes for sockeye smolts. In the first route, the northern route, sockeye smolts migrated quickly northward, across Howe Sound and along the Sunshine Coast to Texada Island. The second route, the western route, includes sockeye moving across the Strait and within the Gulf Islands. Sockeye then migrate north and west through the Strait along Vancouver Island to Texada Island. Sockeye were found to have northward directional tendencies and to prefer the northern route (Grout and Cooke 1987, Grout et.al. 1988 and Peterman 1994, Welch et al. 2009,Melnychuk et al. 2010). Both migration routes continue north of Texada and out of the Strait of Georgia through Johnstone Strait. A small proportion of sockeye are thought to migrate out of the Strait of Juan de Fuca and were found to be primarily comprised of small sized sockeye smolts (Bailey et al. 1988), characterized as river-type sockeye.

Grout and Cooke (1987) suggested sockeye smolts occupy near shore areas, in deeper water during many portions of their migration route. However, extensive sampling conducted by Levings and Kotyk (1983) of foreshore habitats and shoreline margins in Discovery Passage and Lewis, Sutil and Hoskyn channels found very few sockeye smolts in these areas.

Incidental capture of sockeye smolts during trawl surveys for herring in the Strait of Georgia support the use of habitats along migratory corridors previously noted as well as showing additional areas of sockeye smolt habitat use along the eastern Vancouver Island coastline and western Texada Island routes in the Strait of Georgia (Haegele 1997, Haegele et.al. 2005). Sockeye smolts are notably absent from areas including Sechelt Inlet and Agememnon Channel (Levings et.al. 2003).

Adult sockeye return migration is assessed annually through a series of test fisheries in the Strait of Georgia and through acoustic remote sensing during passage in the lower Fraser River (Grant et al. 2010, discussed in Peterman et al. 2010). Adult sockeye use two alternative migration routes through the Strait of Georgia including a southern route through Juan De Fuca Strait with holding areas above the southern Gulf Islands and Fraser plume and estuary, and a second northern diversion route through Johnstone Strait and Discovery Passage along an western route in the Strait of Georgia to holding areas in the Fraser plume and estuary (Gilhousen 1960, Hamilton 1985, Groot and Cooke 1987, Blackbourn 1987, Groot and Quinn 1987, Woodey 1987, Thomson et al. 1992, Levy and Cadenhead 1995, McKinnell et al. 1999, English et al. 2004, Crossin et al. 2004, Hinch et al. 2005). Migration residence periods for an individual migrating adult are often less than 1 month

(Quinn and Harter 1987) in the Strait of Georgia and lower Fraser River dependent on ocean currents (Thomson et al. 1992), during June to September of each year (Hamilton 1985, Woodey 1987). The lower Fraser River is primarily used as a migration corridor for all upstream and lower Fraser River sockeye stocks as passage from the ocean to natal streams of origin.