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Assessment of the risk to Fraser River Sockeye Salmon due to piscine orthoreovirus (PRV) transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

Cardiomyopathy: disturbance or disease of the heart muscle

Clinical: outward appearance of a disease in a living organism

Epidemiological unit: a group of animals that share approximately the same risk of exposure to a pathogenic agent with a defined location

Fish Health Event (FHE): a suspected or active disease occurrence within an aquaculture facility that required the involvement of a veterinarian and any measure that is intended to reduce or mitigate impact and risk that is associated with that occurrence or event

Fomite: an inanimate object capable of transmitting a disease (e.g., contaminated net or boat)

Genogroup: phylogenetically distinct group or cluster

Horizontal transmission: fish to fish transfer of a pathogen

Heart and Skeletal Muscle Inflammation (HSMI): a heart and skeletal muscle inflammatory disease of farmed Atlantic Salmon characterized by cellular epicarditis, moderate-to-severe inflammation and necrosis (especially in the ventricle with inflammation predominant) where inflammation of the red skeletal muscle is a supportive finding; and there is evidence that PRV is a major etiological factor

HSMI-like: inflammatory heart disease as characterized for HSMI but with questionable etiology

Infection: growth of pathogenic microorganisms in the body, whether or not body function is impaired

Infection pressure: concentration of infective pathogens in the environment of susceptible hosts

Mortality event: fish mortalities equivalent to 4000 kg or more, or losses reaching 2% of the current facility inventory, within a 24 hour period; or fish mortalities equivalent to 10,000 kg or more, or losses reaching 5%, within a five day period

Outbreak: the occurrence of one or more cases of a disease than would normally be expected in an epidemiological unit over a given period of time

Prevalence: number of hosts infected with a pathogen (*infection prevalence*) or affected by a disease (*disease prevalence*) expressed as a percentage of the total number of hosts examined for that pathogen (or disease) in a population at a specific time

Subclinical: insufficient signs to cause classical identifiable disease

Sublethal: insufficient to cause death

Susceptible species: a species in which infection has been demonstrated by the occurrence of natural cases or by experimental exposure to the pathogenic agent that mimics natural transmission pathways

Vector: living organism that has the potential to transmit a disease, directly or indirectly, from one animal or its excreta to another animal (e.g., personnel, wildlife, etc.)

ABSTRACT

Fisheries and Oceans Canada, under the Aquaculture Science Environmental Risk Assessment Initiative, is conducting a series of assessments to determine risks to Fraser River Sockeye Salmon due to pathogens on marine Atlantic Salmon farms located in the Discovery Islands area in British Columbia.

This document is the assessment of the risk to Fraser River Sockeye Salmon due to piscine orthoreovirus (PRV) on Atlantic Salmon farms in the Discovery Islands area of British Columbia (BC) under current farm practices which was conducted in three main steps: first, a Likelihood Assessment which is the outcome of four consecutive steps (a farm infection assessment; a release assessment; an exposure assessment; and an overall infection assessment); second, a Consequence Assessment; and third, a Risk Estimation.

PRV, of which only the PRV-1 genogroup is found in the Eastern Pacific, is endemic to BC where it has been detected both in wild and farmed salmon. PRV infections are ubiquitous, highly prevalent and persistent on Atlantic Salmon farms in BC; it is therefore extremely likely with high certainty, that farmed Atlantic Salmon infected with PRV would be present on one or more Atlantic Salmon farm(s) in the Discovery Islands area in given year. Shedding rates from PRV-infected Atlantic Salmon have not yet been quantified; however, laboratory studies provide evidence that infected Atlantic Salmon can shed the virus. It is therefore extremely likely, with high certainty, that PRV could be released from an Atlantic Salmon farm through infected fish. PRV stability in seawater has not been characterized; however, given evidence of temporal overlap between PRV on Atlantic Salmon farms and migration timing of Fraser River Sockeye Salmon in the Discovery Islands area, it is extremely likely, with reasonable certainty, that at least one juvenile and adult Fraser River Sockeye Salmon would be exposed to PRV released from Atlantic Salmon farms in any given year. Finally, under such exposure, given evidence of infection in cohabitation studies, it was concluded that it would be very likely, with high uncertainty, that at least one Fraser River Sockeye Salmon would become infected. Overall, it was concluded that it is very likely that at least one Fraser River Sockeye Salmon would become infected with PRV released from Atlantic Salmon farms in the Discovery Islands area under current farm practices.

The potential magnitude of consequences to the abundance and diversity of Fraser River Sockeye Salmon was considered to be negligible given that current evidence cannot support the conclusion that PRV-1 causes disease or mortality in Sockeye Salmon. This conclusion was made with reasonable certainty and reasonable uncertainty for potential consequences resulting from juvenile and adult infection, respectively.

Overall, the assessment concluded that PRV attributable to Atlantic Salmon farms in the Discovery Islands area poses minimal risk to Fraser River Sockeye Salmon abundance and diversity under the current farm practices. Conclusions have been reached based on a series of rankings estimated with a range of uncertainties. Conclusions should be reviewed as new research findings fill knowledge gaps.

1 INTRODUCTION

Fisheries and Oceans Canada (DFO) has a regulatory role to ensure the protection of the environment while creating the conditions for the development of an economically, socially and environmentally sustainable aquaculture sector. Within this overall objective, DFO's goal for aquaculture is to ensure that fish and their habitats are protected using avoidance, mitigation, monitoring and compliance approaches that are aligned with the potential risk to the environment.

It is recognized that there are interactions between aquaculture operations and the environment (Grant and Jones, 2010; Foreman et al., 2015b). One interaction is the risk to wild salmon populations resulting from the potential spread of infectious diseases from Atlantic Salmon (*Salmo salar)* farms in British Columbia (BC) (Cohen, 2012a).

DFO Aquaculture Management Division requested formal science advice on the risk of pathogen transfer from Atlantic Salmon farms to wild fish populations in BC. Given the complexity of interactions between pathogens, hosts and the environment, DFO is delivering the science advice through a series of pathogen-specific risk assessments to be followed by a synthesis.

This document assesses the risk to Fraser River Sockeye Salmon attributable to piscine orthoreovirus (PRV) from Atlantic Salmon farms in the Discovery Islands area in BC. Risk posed to other wild fish populations and related to other fish farms, pathogens, and regions of BC will be determined through subsequent analyses and are consequently not included in this document.

2 BACKGROUND

This risk assessment is conducted under the DFO Aquaculture Science Environmental Risk Assessment Initiative (hereinafter referred to as the Initiative) implemented as a structured approach to provide science-based risk advice to further support sustainable aquaculture in Canada. Furthermore, to ensure consistency across risk assessments conducted under the Initiative, the Aquaculture Science Environmental Risk Assessment Framework (hereinafter referred to as the Framework) outlines the process and components of each assessment.

The Framework ensures the delivery of systematic, structured, transparent and comprehensive risk assessments. It is consistent with international and national risk assessment frameworks (GESAMP, 2008; ISO, 2009) and has been validated through multiple peer-reviewed processes (Mimeault et al., 2017; Mimeault et al., 2019a; Mimeault et al., 2019b; Mimeault et al., 2019c; Mimeault et al., 2019d). The Framework includes the identification of management protection goals, a problem formulation, a risk assessment and the generation of science advice. The management protection goals and problem formulation were developed in collaboration with DFO's Ecosystems and Oceans Sciences and Ecosystem and Fisheries Management sectors and approved by Aquaculture Management Division.

The Framework also comprises risk communication and a scientific peer-review through DFO's Canadian Science Advisory Secretariat (CSAS) that includes scientific experts both internal and external to DFO. Further details about the Initiative and the Framework are available on the DFO Aquaculture Science Environmental Risk Assessment Initiative webpage.

Risk assessments conducted under this Initiative do not include socio-economic considerations and are not cost-benefit or risk-benefit analyses.

2.1 MANAGEMENT PROTECTION GOALS

In accordance with the recommendations pertaining to aquaculture and fish health in the 2012 final report of the Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (Cohen, 2012a), the valued ecosystem component in this risk assessment is the Fraser River Sockeye Salmon and the management protection goals are to preserve the abundance and diversity of the Fraser River Sockeye Salmon.

2.2 PROBLEM FORMULATION

2.2.1 Hazard identification

In this risk assessment, the hazard is piscine orthoreovirus (PRV) attributable to Atlantic Salmon farms in the Discovery Islands area. Given that PRV-1 is the only genogroup detected in North America to date (Polinski and Garver, 2019), it is the genogroup considered in this risk assessment. Additionally, given differences in the virulence of PRV-1 in Norway compared to Pacific Canada (reviewed in Polinski and Garver (2019)), this risk assessment focuses on PRV-1 found in Pacific Canada. Consequently, all mentions of PRV in this document refer to PRV-1 found in Pacific Canada unless specified otherwise.

2.2.2 Hazard characterization

Polinski and Garver (2019) summarized the relevant characteristics of PRV and of putatively associated pathologies and identified knowledge gaps relevant to this risk assessment.

Polinski and Garver (2019) also included a review of the occurrence of PRV and associated diseases on Atlantic Salmon farms in BC. Additional details specific to Atlantic Salmon farms located in the Discovery Islands area are included in this risk assessment.

2.2.3 Scope

This assessment aims to determine the risk under current farm practices, including regulatory requirements and voluntary practices as described in Wade (2017). It focuses on the risk attributable to Atlantic Salmon farms in the Discovery Islands area (Fish Health Surveillance Zone 3-2) and in close proximity (three farms in Zone 3-3 to the northwest of Zone 3-2) (refer to Figure 1 and Table 1) and includes the same 18 farms as in Mimeault et al. (2017).

Although 18 farms are included, it is worth noting that from December 2010 to February 2016, the number of stocked Atlantic Salmon farms ranged between 3 and 18, with an average of eight farms in any given month (Mimeault et al., 2017). Other Atlantic Salmon farms located along the migratory routes of Fraser River Sockeye Salmon, such as the ones operating in the Broughton Archipelago, are outside the scope of this risk assessment.

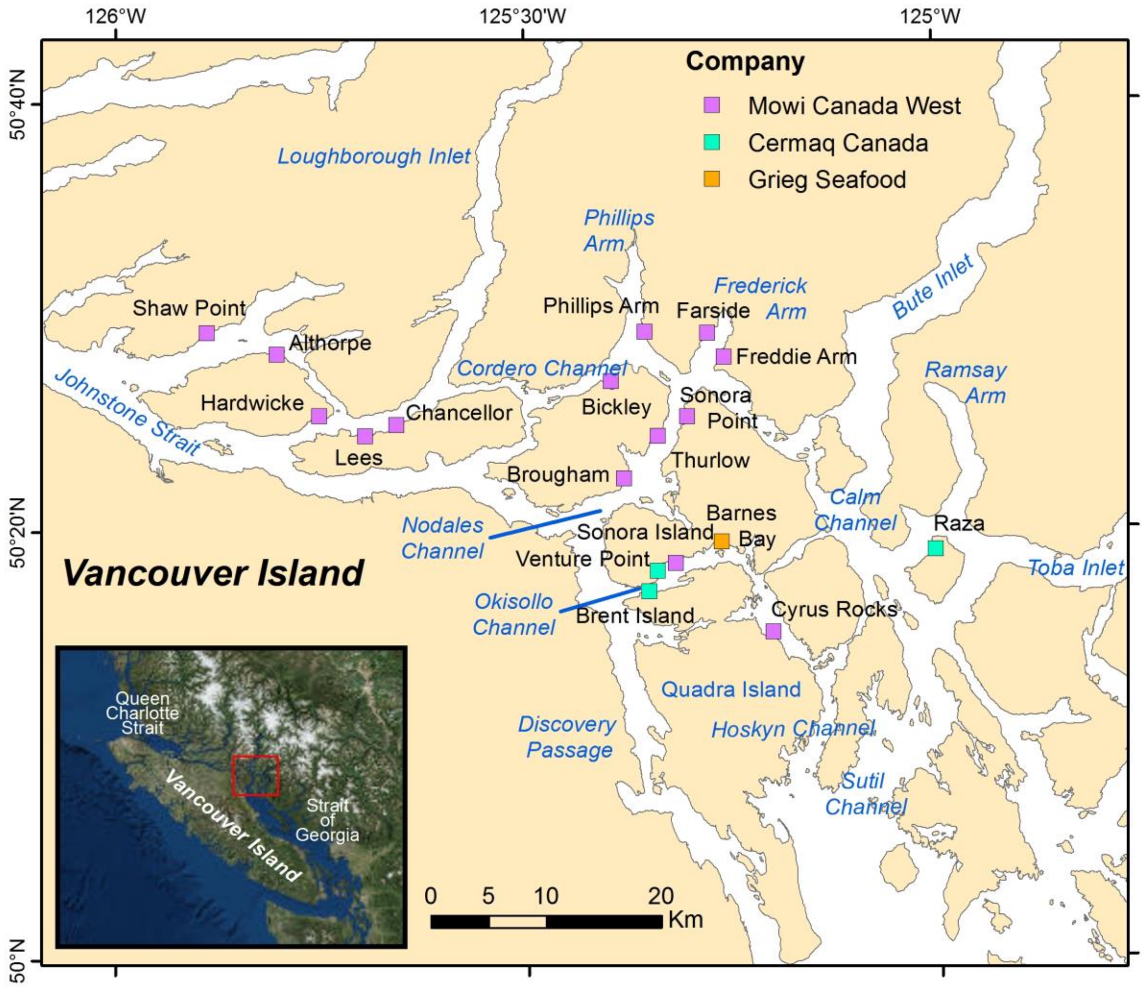

Figure 1. Locations of Atlantic Salmon farms in the Discovery Islands area (Zone 3-2 and three farms in Zone 3-3) included in this risk assessment.Symbol size for fish farms is not to scale. Different colours represent different companies operating the farms as identified in the legend. The insert illustrates the location of the Discovery Islands area in BC. Adapted from Mimeault et al. (2017).

Table 1. List of the 18 Atlantic Salmon farms included in the risk assessment.

Company	Farm	Fish Health Surveillance Zone
Cermaq Canada	Brent Island	3-2
	Raza Island	3-2
	Venture	3-2
Grieg Seafood	Barnes Bay	3-2
Mowi Canada West (formally Marine Harvest Canada)	Althorpe	3-3
	Bickley	3-2
	Brougham Point	3-2
	Chancellor Channel	3-2
	Cyrus Rocks	3-2
	Farside	3-2
	Frederick Arm	3-2
	Hardwicke	3-3
	Lees Bay	3-2
	Phillips Arm	3-2
	Shaw Point	3-3
	Sonora Point	3-2
	Okisollo	3-2
	Thurlow	3-2

This risk assessment focuses on the potential direct impacts of PRV attributable to Atlantic Salmon farms in the Discovery Islands area on Fraser River Sockeye Salmon abundance and diversity. Potential indirect impacts to Fraser River Sockeye Salmon through complex ecosystem processes resulting from infection of other susceptible Pacific salmon species are not considered.

2.2.4 Risk question

What is the risk to Fraser River Sockeye Salmon abundance and diversity due to the transfer of PRV from Atlantic Salmon farms located in the Discovery Islands area under current farm practices?

2.2.5 Methodology

The methodology is based on Mimeault et al. (2017) which was adapted from the DFO Guidelines for Assessing the Biological Risk of Aquatic Invasive Species in Canada (Mandrak et al., 2012), the World Organisation for Animal Health (OIE) Import Risk Analysis (OIE, 2010), recommendations for risk assessments in coastal aquaculture (GESAMP, 2008) and the Food and Agriculture Organisation guidelines on understanding and applying risk analysis in aquaculture (FAO, 2008).

2.2.5.1 Conceptual model

The conceptual model (Figure 2) is adapted from Mimeault et al. (2017) in which the likelihood of an event to take place and its potential magnitude of consequences are combined into a predefined risk matrix to estimate the risk. The likelihood is assessed in four consecutive steps namely: a farm infection assessment; a release assessment; an exposure assessment; and an infection assessment. The consequence assessment determines the potential magnitude of impacts of PRV infection attributable to Atlantic Salmon farms in the Discovery Islands area on the abundance and diversity of Fraser River Sockeye Salmon.

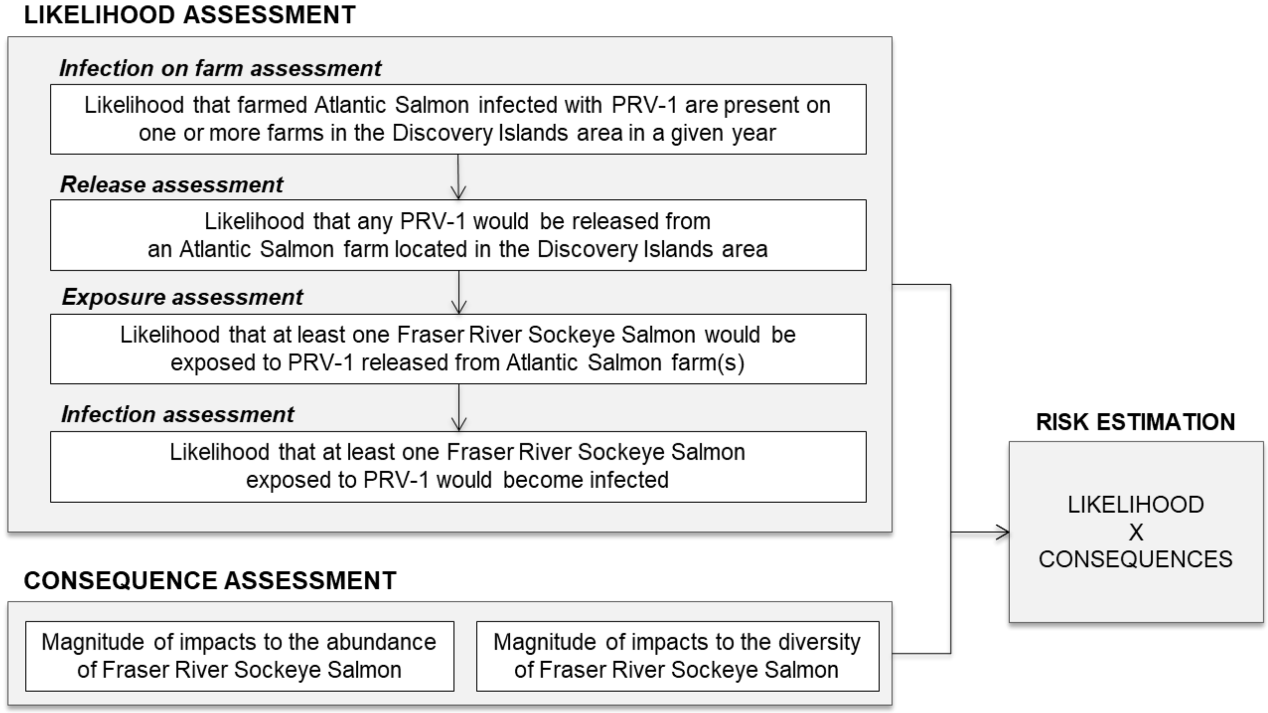

Figure 2. Conceptual model to assess the risks to Fraser River Sockeye Salmon resulting from piscine orthoreovirus-1 (PRV-1) attributable to Atlantic Salmon farms in the Discovery Islands area, BC. Adapted from Mimeault et al. (2017).

2.2.5.2 Terminology

The categories and definitions used to rank likelihood (Table 2), consequences to abundance (Table 3), consequences to diversity (Table 4), uncertainty for data and information (Table 5) and uncertainty for fish health management (Table 6) were adapted from Mimeault et al. (2017).

Table 2. Categories and definitions used to describe the likelihood of an event over a period of a year. "Extremely unlikely" is the lowest likelihood and "extremely likely" is the highest likelihood. Adapted from Mimeault et al. (2017).

Categories	Definitions
Extremely unlikely	Event has little to no chance to occur
Very unlikely	Event could occur rarely
Unlikely	Event could occur occasionally
Likely	Event will usually occur
Very likely	Event will occur in most instances
Extremely likely	Event will occur/is expected to occur

Table 3. Categories and definitions used to describe the potential consequences to the abundance of Fraser River Sockeye Salmon. Adapted from Mimeault et al. (2017).

Categories	Definitions
Negligible	0 to 1% reduction in the number of returning Fraser River Sockeye Salmon
Minor	> 1 to 5% reduction in the number of returning Fraser River Sockeye Salmon
Moderate	> 5 to 10% reduction in the number of returning Fraser River Sockeye Salmon
Major	> 10 to 25% reduction in the number of returning Fraser River Sockeye Salmon
Severe	> 25 to 50% reduction in the number of returning Fraser River Sockeye Salmon
Extreme	> 50% reduction in the number of returning Fraser River Sockeye Salmon

Table 4. Categories and definitions used to describe the potential consequences to the diversity of Fraser River Sockeye Salmon. CU: Conservation Unit. Adapted from Mimeault et al. (2017).

Categories	Definitions
Negligible	0 to 1% change in abundance over a generation and no loss of Fraser River Sockeye Salmon CUs over a generation
Minor	> 1 to 10% reduction in abundance in some CUs that would not result in the loss of a Fraser River Sockeye Salmon CU over a generation
Moderate	1 to 10% reduction in abundance in most conservation units that would not result in the loss of a Fraser River Sockeye Salmon CU over a generation; OR > 10 to 25% reduction in abundance in one or more CUs that would not result in the loss of a Fraser River Sockeye Salmon CU over a generation
Major	> 25% reduction in abundance in one or more CUs that would not result in the loss of a Fraser River Sockeye Salmon CU over a generation
Severe	Reduction in abundance that would result in the loss of a Fraser River Sockeye Salmon CU over a generation
Extreme	Reduction in abundance that would result in the loss of more than one Fraser River Sockeye Salmon CU over a generation

Table 5. Categories and definitions used to describe the level of uncertainty associated with data and information.Taken from Mimeault et al. (2017).

Categories	Definitions
High uncertainty	• No or insufficient data • Available data are of poor quality • Very high intrinsic variability • Experts' conclusions vary considerably
Reasonable uncertainty	• Limited, incomplete, or only surrogate data are available • Available data can only be reported with significant caveats • Significant intrinsic variability • Experts and/or models come to different conclusions
Reasonable certainty	• Available data are abundant, but not comprehensive • Available data are robust • Low intrinsic variability • Experts and/or models mostly agree
High certainty	• Available data are abundant and comprehensive • Available data are robust, peer-reviewed and published • Very low intrinsic variability • Experts and/or models agree

Table 6. Categories and definitions used to describe the level of uncertainty associated with fish health management. "Some" and "most" are respectively defined as less and more than 50% of relevant data. Taken from Mimeault et al. (2017).

Categories	Definitions
High uncertainty	• No information collected through farm management practices, as specified in Salmonid Health Management Plans, is available • Discrepancy between information/data obtained through farms and farm audits for all farms • Voluntary farm practice(s) • Expert opinion varies considerably
Reasonable uncertainty	• Some information collected through farm management practices, as specified in Salmonid Health Management Plans, is available • Discrepancy between information/data obtained through farms and farm audits for most farms • Voluntary company practice(s) • Experts come to different conclusions
Reasonable certainty	• Most information collected through farm management practices, as specified in Salmonid Health Management Plans, is available • Corroboration between information/data obtained through farms and farm audits for most farms • Voluntary industry-wide practice(s) agreed through a Memorandum of Understanding or certification by a recognized third party • Experts mostly agree
High certainty	• All information collected through farm management practices, as specified in Salmonid Health Management Plans, is available • Corroboration between information/data obtained through farms and farm audits for all farms • Mandatory practice(s) required under legislation and certification by a recognized third party • Experts agree

2.2.5.3 Combination rules

As described in Mimeault et al. (2017), the combination of likelihoods differs if events are dependent or independent: "An event is dependent when its outcome is affected by another event. For example, infection can only happen if exposure took place, consequently infection is dependent on exposure. Events are independent when the outcome of one event does not affect the outcome of other event(s); for example, a pathogen can be released into the environment via different unrelated pathways". Likelihoods are combined as per accepted methodologies in qualitative risk assessments adopting the lowest value (e.g., low) for dependent events and the highest value (e.g., high) for independent events (Cox, 2008; Gale et al., 2010; Cudmore et al., 2012).

Uncertainties are reported at each step of the risk assessment. Several approaches have been used for combining qualitative uncertainty rankings in risk assessments. Some authors report uncertainty for every step without combination (Peeler and Thrush, 2009; Jones et al., 2015), others adopt the highest uncertainty (Mandrak et al., 2012) while finally others adopt the highest uncertainty associated with the lowest likelihood for dependent events (Cudmore et al., 2012). In this risk assessment, uncertainties are not combined in the overall likelihood and consequence assessments to keep the emphasis on the uncertainty associated to each step.

2.2.5.4 Risk estimation

As described in Mimeault et al. (2017), two risk matrices were developed in collaboration with DFO's Ecosystems and Oceans Sciences and Ecosystem and Fisheries Management sectors to categorize the risk estimates for the abundance (Figure 3) and diversity (Figure 4) of Fraser River Sockeye Salmon. They are aligned with relevant scale of consequences for fisheries management and policy purposes, existing policy and current management risk tolerance relevant to the risk assessments.

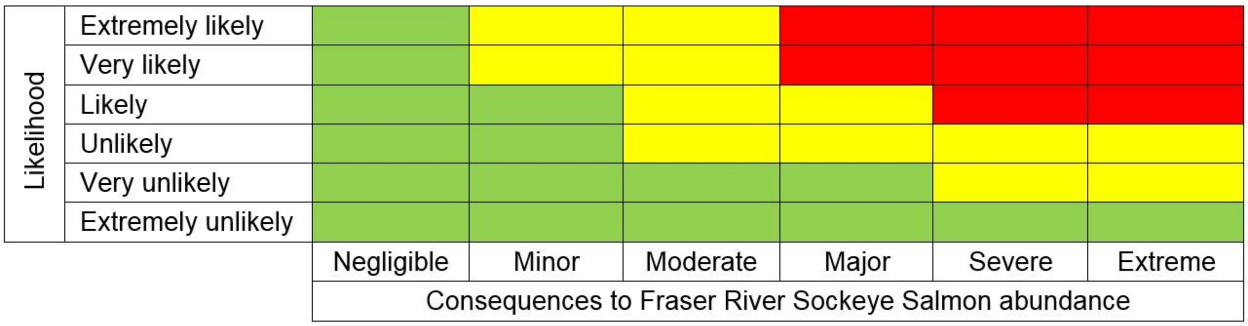

Figure 3. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon abundance. Green, yellow and red, respectively, represent minimal, moderate and high risk.

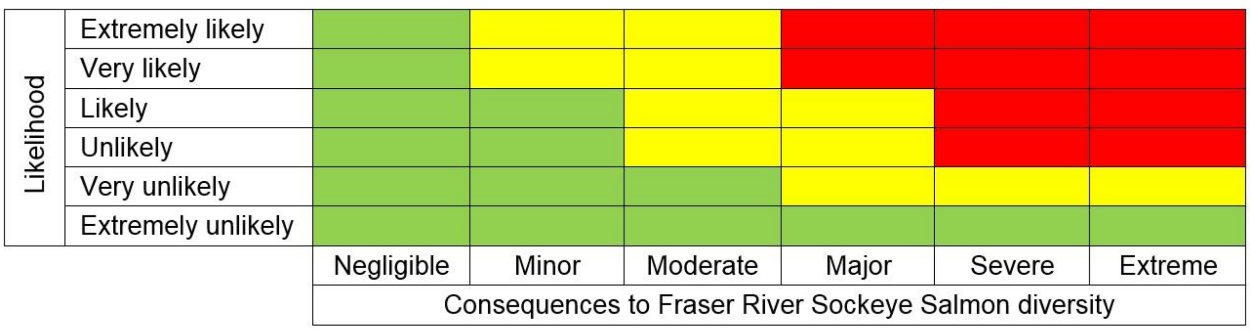

Figure 4. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon diversity. Green, yellow and red, respectively, represent minimal, moderate and high risk.

3 LIKELIHOOD ASSESSMENT

The likelihood assessment consists of determining the likelihood that Fraser River Sockeye Salmon would become infected with piscine orthoreovirus (PRV) attributable to Atlantic Salmon farms located in the Discovery Islands area.

Each step of the likelihood assessment assumes that current management practices on Atlantic Salmon farms are followed and will be maintained.

3.1 FARM INFECTION ASSESSMENT

3.1.1 Question

In a given year, what is the likelihood that farmed Atlantic Salmon infected with PRV are present on one or more farms in the Discovery Islands area?

3.1.2 Considerations

Considerations include evidence of Atlantic Salmon susceptibility to PRV; regulatory requirements; industry practices; PRV prevalence in hatcheries; and PRV on Atlantic Salmon farms in the Discovery Islands area.

3.1.2.1 Atlantic Salmon susceptibility to PRV infection

PRV genetic material has been detected in Atlantic Salmon in several countries (Palacios et al., 2010; Kibenge et al., 2013; Marty et al., 2015; Adamek et al., 2018; Gunnarsdóttir et al., 2018; Markussen et al., 2018; Warheit, 2018).

More specifically, Atlantic Salmon infection with the PRV-1 genetic type from Pacific Canada has been demonstrated through a cohabitation study (Garver et al., 2016a) and PRV has been reported on Atlantic Salmon farms in BC (Marty et al., 2015; Di Cicco et al., 2017; Laurin et al., 2019) demonstrating Atlantic Salmon susceptibility to PRV infection.

3.1.2.2 Regulatory requirements

3.1.2.2.1 Licensing and biosecurity

DFO has had the primary responsibility for the regulation and management of aquaculture in BC since December 2010 through the Pacific Aquaculture Regulations (PAR) developed under the Fisheries Act. DFO is therefore responsible for issuing aquaculture licenses for marine finfish, shellfish and freshwater operations in BC.

Each farm operating in BC requires a Finfish Aquaculture Licence under the PAR which includes the requirement for a Salmonid Health Management Plan (SHMP) and accompanying proprietary Standard Operating Procedures (SOPs) (DFO, 2015). The SHMP outlines the health concepts and required elements associated with a finfish aquaculture licence, while accompanying SOPs detail the procedures to address specific concepts of the SHMP including monitoring fish health and diseases (DFO, 2015; Wade, 2017).

The SHMP includes requirements related to “Keeping Pathogens Out” (section 2.5 of the SHMP) (DFO, 2015) including that particular care be taken to avoid undue fish stress and transmission of pathogens and also requires a licence by the Introductions and Transfer Committee in advance of any fish transfers (DFO, 2015).

3.1.2.2.2 Fish Health Audit and Surveillance Program

Samples from recently dead fish are collected through the Fish Health Audit and Surveillance Program (hereinafter referred to as the audit program) to audit the routine monitoring and reporting of diseases by the farms (Wade, 2017). Moribund fish can also be sampled (I. Keith, DFO, 103-2435 Mansfield Drive, Courtenay, BC V9N 2M2, pers. comm., 2018). DFO aims to audit 30 randomly selected farms per quarter or 120 farms per year (Wade, 2017).

During an audit, a maximum of 30 fresh fish are selected for histopathology, bacteriology and molecular diagnostics/virology, although in most circumstances eight fresh fish are sampled (Wade, 2017). DFO veterinarians provide farm-level diagnoses based on a combination of farm history, treatment history, environmental factors, mortality records, clinical presentation on farm and results of diagnostic procedures performed on individual fish (DFO, 2018c).

PRV is not included in the molecular diagnostics completed on audit samples.

3.1.2.2.3 Fish Health Events

Fish Health Events (FHEs) are reported to DFO by the industry. DFO (2015) defines a FHE as "a suspected or active disease occurrence within an aquaculture facility that requires the involvement of a veterinarian and any measure that is intended to reduce or mitigate impact and risk that is associated with that occurrence or event". When a FHE occurs, the licence holder must take action to manage the event, evaluate the mitigation measures, submit a notification of FHE and therapeutic management measures to the Department (DFO, 2015).

Reporting of FHEs has been required since the fall of 2002 with the exception of 2013, 2014 and first three quarters of 2015 during which mortalities had to be reported by cause (Wade, 2017). During this time, FHEs were still reported to the BC Salmon Farmers Association (BCSFA) but were not required to be reported to DFO as a condition of licence. The BCSFA provided the missing FHEs on Atlantic Salmon farms in the Discovery Islands area to inform this assessment.

No FHEs attributed to a PRV infection have ever been reported on Atlantic Salmon farms in the Discovery Islands area.

3.1.2.2.4 Mortality Events

DFO (2015) defines a mortality event as "a) fish mortalities equivalent to 4000 kg or more, or losses reaching 2% of the current facility inventory, within a 24 hour period; or (b) fish mortalities equivalent to 10,000 kg or more, or losses reaching 5%, within a five day period". As a condition of licence, any mortality event must be reported to DFO no later than 24 hours after discovery with details including facility name, fish cultured, number of dead fish, suspected proportion affected, suspected carcass biomass, probable cause, and action taken (DFO, 2015).

To date, no mortality events attributed to a PRV infection, or to any infectious diseases, have even been reported on Atlantic Salmon farms in the Discovery Islands area.

3.1.2.2.5 Introduction and Transfer Committee

DFO grants Introduction and Transfer licenses under Section 56 of the Fishery (General) Regulations. The Introductions and Transfers Committee (ITC) assesses the health, genetic and ecological impacts that could occur through the transfer of fish into and within the Province. A Section 56 introductions and transfers licence is required for all movements of salmon between licensed aquaculture facilities (DFO, 2018b). For the aquaculture industry, the committee assesses the health of fish to be transferred which includes the diseases and causative agents of regional, national or international concern as listed in Appendix III[1] of the Marine Finfish Aquaculture Licence under the Fisheries Act, along with any other concern that may arise during the assessment.

For every aquaculture related transfer application, fish health reports and husbandry records are examined by Aquaculture Management Division staff prior to transfer. If any clinical signs of diseases are seen, or there are any other concerns, the committee can either recommend that the transfer should not happen, or they can work with the applicant to ensure the transfer is

[1] In 2018, diseases of regional, national or international concern listed in the Marine Finfish Aquaculture Licence under the Fisheries Act are Infectious Hematopoietic Necrosis (IHN) and infectious hematopoietic necrosis virus; Infectious Pancreatic Necrosis (IPN) and infectious pancreatic necrosis virus; Viral Hemorrhagic Septicemia (VHS) and viral hemorrhagic septicemia virus; Infectious Salmon Anemia (ISA) and infectious salmon anemia virus; *Oncorhynchus masou* Virus Disease (OMV) and *Oncorhynchus masou* virus; Whirling Disease and *Myxobolus cerebralis*; Cold Water Vibriosis and *Vibrio salmonicida*; and any other filterable replicating agent causing cytopathic effects in cell lines specified by the Minister or is causative of identifiable clinical disease in fish.

carried out in a safe manner. Currently, there are no requirements to test for PRV prior to the transfer of fish into marine net pens or between sites (M. Higgins, Fisheries and Oceans Canada, pers. comm., 2018).

3.1.2.3 Industry practices

Companies rearing Atlantic Salmon on marine sites in the Discovery Islands area are Cermaq Canada, Grieg Seafood and Mowi Canada West (formally Marine Harvest Canada). Refer to Wade (2017) for an overview of health management practices on Atlantic Salmon farms in BC.

3.1.2.3.1 Movement of live fish

Between January 2013 and December 2017, Atlantic Salmon have been present on farms in the Discovery Islands area throughout the year (Appendix A, Figure 6). The duration of farmed Atlantic Salmon production cycles in the Discovery Islands area over the same period ranged between 12 and 23 months (average=17 months, n=27 cycles) from the beginning of stocking to the end of harvesting periods.

In the Discovery Islands area, smolts are not transferred directly from freshwater hatcheries to marine sites due to the risk of infection from *Kudoa* sp., a parasite of marine fishes (Wade, 2017) with the exception of Raza where *Kudoa* sp. has not been an issue (Danielle New, Cermaq Canada, 203-919 Island Highway, Campbell River, BC, Canada V9W 2C2, pers. comm., 2018).

Fish transfers to marine grow-out sites in the Discovery Islands area occurred every month of the year (Appendix A, Figure 7). Fish reared in this area can previously spend between 2 to 14 months (average=7 months, n=23 cycles) on a marine nursery site before being transferred to a grow-out site.

3.1.2.3.2 Surveillance and testing

Every stocked marine production site is monitored daily by on-site trained staff for syndromic surveillance during which mortalities are removed and classified. Staff alerts the veterinarian if there are any concerns. Additionally, routine health checks are conducted regularly by all companies during which fresh mortalities and/or silvers are examined for signs of diseases or abnormal conditions and sampled for pathogen screening on an as needed basis based on syndromic surveillance, site history, environmental conditions and professional judgement of the veterinarian and fish health team. The frequency of routine health checks and sampling for pathogen screening varies among companies as described below.

In addition to daily monitoring, every Cermaq Canada stocked marine production site is visited by fish health staff or the veterinarian a minimum of once every two weeks to confirm on-site mortality classification and to sample up to five moribund or fresh mortalities with no obvious cause of death (e.g., non-performing, algae, handling, low oxygen, matures, deformities) (B. Milligan, Cermaq Canada, pers. comm., 2018).

In addition to daily monitoring, every Grieg Seafood stocked marine production site is visited at least once every quarter by the fish health staff and/or veterinarian where at least five silvers are sampled for bacteriology, histology and PCR testing (P. Whittaker and T. Hewison, Grieg Seafood, pers. comm., 2018).

In addition to daily monitoring, every Mowi Canada West stocked production site is visited at least once a month by fish health staff or the veterinarian and at least once every quarter by the veterinarian. Fresh mortalities and/or silver samples may be collected for pathogen screening based on syndromic surveillance, site history, environmental conditions and professional judgement of the veterinarian and the fish health team (D. Morrison, Mowi Canada West, pers. comm., 2018).

3.1.2.3.3 Vaccination and treatment

There is no commercial vaccine available for PRV nor are there treatments available for PRV-infected Atlantic Salmon. There are no data to suggest that PRV adversely affects aquaculture production of salmon in BC (Polinski and Garver, 2019).

3.1.2.4 PRV detections in Atlantic Salmon hatcheries

Atlantic Salmon in hatcheries are screened for PRV as part of research by the industry into the prevalence of PRV in their fish (R. Salmon, BCSFA, #201-911 Island Highway, Campbell River, BC V9W 2C2, pers. comm., 2019). Screened fish are a mix of moribund and healthy individuals. Table 7 summarizes PRV screening results on fish sampled prior to transfer to seawater and rearing in the Discovery Islands area which represents a proportion of the overall hatchery PRV screening conducted by the industry.

Between 2013 and 2018, PRV has been detected in some hatcheries, with percent PRV positive sampled fish ranging between 0.2 to 72.5%. The trends show an increase in the number of samples collected during this period and a decrease in the percentage of PRV positive sampled fish. Prior to 2016, screening tools for PRV were not widely available and the industry did not have a focus on this virus, which is reflected in the low number of fish screened prior to 2016 (R. Salmon, BCSFA, pers. comm., 2019).

Table 7. PRV screening conducted between 2013 and 2018 in Atlantic Salmon in hatcheries prior to transfers destined to marine sites in the Discovery Islands area, BC. Results only include last sampling events prior to transfer to seawater. Screened fish are a mix of moribund and healthy individuals. Source: Data provided by the industry in January 2019.

Year	Number of fish* (hatcheries) screened for PRV	Number of PRV positive fish (hatcheries)	Percent PRV positive fish
2013	48 (2)	20 (1)	41.7
2014	40 (2)	29 (2)	72.5
2015	110 (2)	29 (1)	26.4
2016	189 (5)	21 (2)	11.1
2017	370 (8)	3 (1)	0.8
2018	584 (8)	1 (1)	0.2

** Three sampling events (two in 2015 and one in 2016), out of a total of 42 sampling events (2013-2018), had unspecified number of fish for which 25 fish per sampling event were assumed.*

3.1.2.5 PRV detections on Atlantic Salmon farms in BC

Several studies have reported PRV on Atlantic Salmon farms in BC (Marty et al., 2015; Di Cicco et al., 2017; Laurin et al., 2019).

Marty et al. (2015) reported 95% (35/37) of archived samples of farmed Atlantic Salmon collected between 2000 and 2008 from DFO management areas 7, 12 ,13 and 18 (respectively Prince and Hunter Islands; Northern Johnstone Strait; Quadra and Cortes Islands; and Mayne Island, Saanich) and 100% (20/20) of Atlantic Salmon sampled in 2013 from a marine rearing site in the Northern Johnstone Strait approximately one month after transfer from a hatchery, to be PRV positive. Samples collected in 2013 were from the live population, authors provided no details for the 2000-2008 archives samples.

Di Cicco et al. (2017) sampled live, moribund and recently dead Atlantic Salmon on a farm in BC. Three to four months after seawater transfer (in August and September 2013), PRV prevalence in sampled fish ranged between 15 and 19%. PRV prevalence increased to approximately 88% after five months in seawater (October 2013), reached 100% after six months (November 2013) in seawater and remained at 100% after almost eight months (January 2013) in seawater. Refer to Di Cicco et al. (2017) for details about sample size.

Laurin et al. (2019) reported 67% (448/668) of all recently dead and moribund Atlantic Salmon sampled through the audit program between April 2011 and December 2013 on farms across BC to be PRV positive; a proportion that varied approximately from 40% to nearly 90% among different fish health zones in BC. Time-at-sea was a significant predictor for PRV detection in Atlantic Salmon with the highest odds of detecting the virus reported 12 to 18 months after transfer to seawater (Laurin et al., 2019).

In on-going research examining PRV prevalence in live, moribund and/or recently dead Atlantic Salmon on 13 farms in BC, including in the Discovery Islands area, all sites became PRV positive with a general onset between approximately 100 to 200 days after seawater entry and 100% of samples (132/132) collected from fish at sea for more than 296 days were PRV positive (Polinski and Garver, unpublished data reported in Polinski and Garver (2019)).

PRV screening results provided by the industry to support this risk assessment also indicate that most fish become infected with the virus at some point in the marine grow-out phase.

Regardless of the methodology used and test performance characteristics, overall, based on the above studies and information, evidence demonstrates that PRV is ubiquitous, highly prevalent and persistent on Atlantic Salmon farms in BC.

3.1.3 Assumptions

- Positive detection of the pathogen is evidence of infection; and
- Results from research studies throughout all zones are representative of the Discovery Islands area.

3.1.4 Likelihood of farm infection

Table 8 presents the main factors contributing to and limiting the likelihood of a PRV infection occurring on an Atlantic Salmon farm in the Discovery Islands area. Those factors were used to determine the likelihood and uncertainty rankings based on definitions in Tables 2, 5 and 6.

Table 8. Factors contributing to and limiting the likelihood that farmed Atlantic Salmon infected with piscine orthoreovirus-1 are present on one or more Atlantic Salmon farms in the Discovery Islands area under the current farm practices.

Contributing factors	Limiting factors
• Atlantic Salmon are susceptible to PRV infection; • All Atlantic Salmon farms in the Discovery Islands area are anticipated to become infected with PRV within 100-200 days post-seawater transfer; • Independent of farm location or season of transfer to seawater, Atlantic Salmon farms become infected with PRV and can reach 100% prevalence; • In the Discovery Islands area, except for one site, smolts are transferred from other marine rearing sites; • Smolts may be held from 2 to 14 months in marine nursery sites before transfer to Discovery Islands area; and • Current regulatory requirements for an aquaculture-related BC introduction and transfers licence are related to clinical signs of disease and/or the detection of the causative agents listed in Appendix III of the Marine Finfish Aquaculture Licence under the Fisheries Act which does not include PRV.	• Hatchery-origin infection is mitigated through egg disinfection, a requirement of the SHMP and other biosecurity practices.

It was concluded that, in a given year, the likelihood that farmed Atlantic Salmon infected with PRV are present on one or more Atlantic Salmon farms in the Discovery Islands area is **extremely likely** under the current farm practices given the evidence of PRV infection on Atlantic Salmon farms following seawater transfer. This conclusion was made with **high certainty** given abundant and robust data demonstrating PRV infections on Atlantic Salmon farms in BC.

3.2 RELEASE ASSESSMENT

3.2.1 Question

Assuming that Atlantic Salmon infected with PRV are present, what is the likelihood that any PRV would be released from an Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to Fraser River Sockeye Salmon?

3.2.2 Considerations

Considerations include Atlantic Salmon rearing conditions in the Discovery Islands area; shedding of PRV from infected fish; and fish health management practices.

3.2.2.1 Atlantic Salmon rearing methods

Atlantic Salmon reared on marine sites in the Discovery Islands area are contained in net pens. Under such conditions, water flows freely through the cages and there are no barriers to pathogen exchanges between the net pens and the environment (Johansen et al., 2011).

3.2.2.2 Shedding of PRV from infected fish

Polinski and Garver (2019) reviewed the state of knowledge related to shedding in PRV-infected fish. Given evidence of horizontal transmission during cohabitation study (Garver et al., 2016a), PRV infected salmon are considered to be a source of the virus (Polinski and Garver, 2019). PRV has been detected in faecal contents of Atlantic Salmon challenged through injections or anal intubation with a PRV inoculum originating from Norwegian field heart and skeletal muscle inflammation (HSMI) outbreak (Hauge et al., 2016). The above studies provide evidence that PRV-infected fish can shed the virus into the surrounding environment.

To this date, the rate of shedding from PRV-infected Atlantic Salmon (or other salmonids) has not been quantified (Polinski and Garver, 2019). However, based on cohabitation studies (Garver et al., 2016a; Polinski et al., 2019), it is hypothesized that horizontal transmission primarily occurs between 3 to 15 weeks following infection, after which the potential for natural shedding becomes severely reduced despite persistence of infection (Polinski and Garver, 2019).

3.2.2.3 Fish health management practices

All licence holders must comply with the Health Management Plan which includes biosecurity measures to maintain fish health, prevent pathogen entry and limit the spread of diseases on farm (DFO, 2015).

The Salmonid Health Management Plan (SHMP) requires procedures for collecting, categorizing, recording, storing and disposing of fish carcasses (DFO, 2015). More specifically, procedures must be in place for the regular removal of carcasses to storage containers; the reporting of mortality by category to DFO; a secure location of stored carcasses until transfer to land-based facilities; to prevent contents from leaking into the receiving waters; the secure transfer of stored carcasses to land-based facilities; and sanitization methods for storage containers, equipment and other handling facilities or vessels (DFO, 2015). The SHMP also requires a SOP for fish disease outbreaks or emergency, where an outbreak is defined as an "unexpected occurrence of mortality or disease" (DFO, 2015).

Beyond indicating if a SOP is required, DFO does not prescribe how elements of the SHMP should be achieved. It is therefore up to the company to address the concepts to the satisfaction of the DFO's fish health veterinarian (Wade, 2017). Consequently, it is assumed that for companies with a valid finfish aquaculture licence, the SOPs submitted are in compliance with the conditions of licence and approved by the DFO veterinarian (Wade, 2017).

Protocols are in place for handling and storing dead fish; for labeling, cleaning, disinfecting and storing gear used to handle dead fish; to restrict visitors who must obtain permission prior to arriving on site; to control on-site visitors through the use of signage, footbaths and site specific protective clothing; net washing procedures, not sharing equipment when possible, cleaning and disinfecting equipment after use and dry storing in proper locations; for cleaning, disinfecting and transferring large and submerged equipment among sites; and biosecurity measures to control vessel movement (Wade, 2017).

Compliance with the above elements is determined through the audit program. On average, less than one deficiency has been reported per audit on Atlantic Salmon farms in BC between 2011 and 2017 (Appendix B, Table 15). Most deficiencies reported in this period were related to sea lice protocols and sea lice records; carcass retrieval protocol or record keeping that requires improvement; mooring signage needing improvement; and transfer records not being complete.

3.2.3 Assumptions

- Atlantic Salmon infected with PRV are present on at least one farm; and
- Biocontainment measures are effective against PRV (e.g., Virkon footbaths, etc.).

3.2.4 Likelihood of release

Table 9 presents the main factors contributing to and limiting the likelihood that PRV would be released from an infected Atlantic Salmon farm in the Discovery Islands area. These factors were used to determine the likelihood and uncertainty rankings based on definitions in Tables 2, 5 and 6.

Table 9. Factors contributing to and limiting the likelihood that any piscine orthoreovirus-1 would be released from an Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to Fraser River Sockeye Salmon under the current farm practices.

Contributing factors	Limiting factors
• PRV-infected Atlantic Salmon can shed the virus into the surrounding environment; and • Atlantic Salmon in the Discovery Islands area are reared in net pens allowing pathogens, including PRV, to be released from the farms to the surrounding environment.	• Protocols are in place for handling and storing dead fish; for labeling, cleaning, disinfecting and storing gear used to handle dead fish; • Protocols are in place to restrict visitors who must obtain permission prior to arriving on site and to control on-site visitors through the use of signage, footbaths and site specific protective clothing; • Protocols are in place to minimize predators and wildlife access; • Protocols are in place for net washing procedures, not sharing equipment when possible, cleaning and disinfecting equipment after use and dry storing in proper locations; • Protocols are in place for cleaning, disinfecting and transferring large and submerged equipment among sites; • Biosecurity measures are in place to control vessel movement; and • Low levels of operational deficiencies that could affect fish health have been reported on Atlantic Salmon farms in the Discovery Islands area.

Two pathways were considered in the release assessment: (1) infected farmed Atlantic Salmon and (2) vectors and fomites.

3.2.4.1 Release through infected farmed Atlantic Salmon

It was concluded that the likelihood that PRV would be released from an Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to Fraser River Sockeye Salmon through infected farmed Atlantic Salmon is **extremely likely** under the current farm practices given rearing of Atlantic Salmon in net pens and evidence that infected Atlantic Salmon can shed the virus. This conclusion was made with **high certainty** based on robust published laboratory studies on horizontal transfer and infection through cohabitation studies.

3.2.4.2 Release through vectors and fomites

It was concluded that the likelihood that PRV would be released from an Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to wild fish populations through vectors or fomites is **unlikely** under the current farm practices. This conclusion was made with **reasonable uncertainty** given relevant biosecurity practices are part of licence requirements and low levels of operational deficiencies that could affect fish health on Atlantic Salmon farms in the Discovery Islands area but also given the use of proxy data and assumption that biocontainment practices are effective against PRV.

3.2.4.3 Overall likelihood of release

The overall likelihood of release was obtained by adopting the highest likelihood of the release pathways. It is therefore **extremely likely** that PRV would be released from an Atlantic Salmon farm should it become infected.

3.3 EXPOSURE ASSESSMENT

3.3.1 Question

Assuming that PRV has been released from at least one Atlantic Salmon farm in the Discovery Islands area, what is the likelihood that at least one Fraser River Sockeye Salmon would be exposed to PRV in a given year?

3.3.2 Considerations

The exposure assessment consists of determining the spatial and temporal concurrence of the released pathogen and susceptible species (Taranger et al., 2014).

Considerations include size and volume of Atlantic Salmon farms; occurrence of Fraser River Sockeye Salmon in the Discovery Islands area; timing of PRV on Atlantic Salmon farms; survival of PRV in the marine environment; and concurrence of PRV and Fraser River Sockeye Salmon.

3.3.2.1 Size and volume of Atlantic Salmon farms

The likelihood of Fraser River Sockeye Salmon to encounter Atlantic Salmon farms on their migration routes should take into account the relative size and volume of farms in the area and within channels.

Atlantic Salmon farms in the Discovery Islands area occupy an extremely small area (0.007%) and volume (0.0008%) of the overall region (Mimeault et al., 2017). Considering that channel width in the Discovery Islands area varies between approximately 850 and 3,200 meters (Mimeault et al., 2017), a farm with dimension of 100 m by 100 m by 20 m depth would span over approximately 3 to 12% of the width of the channel (Figure 5).

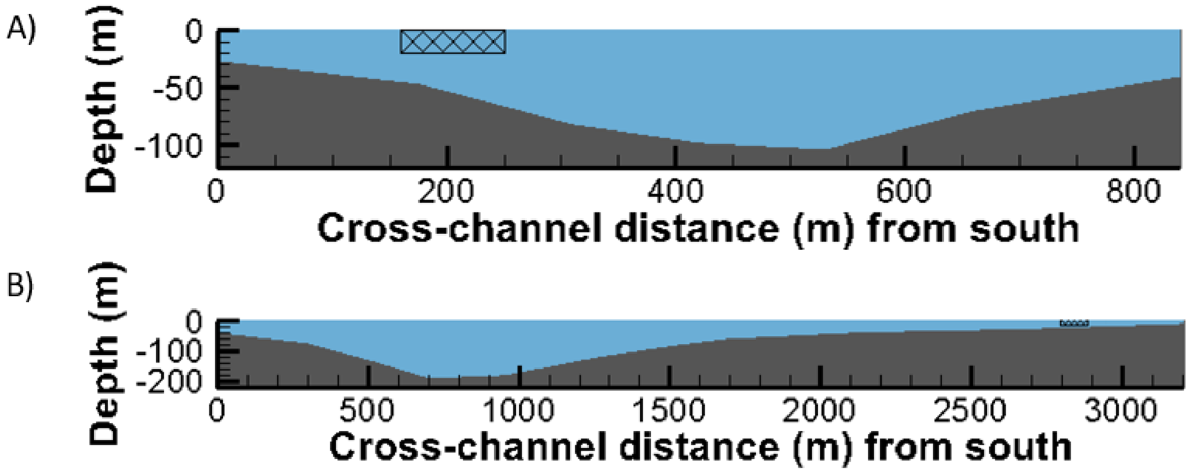

Figure 5. Cross sections of channels at (A) Brent and (B) Shaw farms located in respectively the narrowest and widest channel with Atlantic Salmon farms in the Discovery Islands area. Cross-hatched boxes show the cross-channel projection of the net-pens of the farms depicted at scale, i.e., what fish swimming along-channel would encounter. Note the difference in the ranges on the axes to maintain constant ratio (one:one) between the x and y axes in each cross section. Adapted from Mimeault et al. (2017).

3.3.2.2 Fraser River Sockeye Salmon in Discovery Islands area

3.3.2.2.1 Juveniles

Juvenile Fraser River Sockeye Salmon migrate through the Discovery Islands area every year from mid-May to mid-July (reviewed in Grant et al., 2018). The total number of juveniles out-migrating from the Fraser River is unknown (Grant et al., 2018). The only estimate of abundance is limited to stocks from Chilko Lake (Grant et al., 2018) based on smolts enumerated at a counting fence located at the outlet of the lake; between 1953 and 2007, annual estimates of Chilko Lake one-year-old smolts ranged between 1.6 to 77 million (average: 20 million) (Grant et al., 2018).

3.3.2.2.2 Adults

Between 1980 and 2014, the total adult returns of Fraser River Sockeye Salmon ranged from 2 to 28 million, with an annual average of 9.6 million (Grant et al., 2018).

3.3.2.3 Timing of PRV on Atlantic Salmon farms

PRV has been reported on Atlantic Salmon farms in BC (Marty et al., 2015; Di Cicco et al., 2017; Laurin et al., 2019). Refer to the Farm Infection Assessment section for more details on PRV prevalence. Of relevance to the exposure assessment is the timing of PRV detections on Atlantic Salmon farms in the Discovery Islands area.

PRV was detected in Atlantic Salmon sampled in the month of April 2013 on a marine rearing site in BC (Marty et al., 2015); in the months of August through November 2013 and January 2014 on a marine rearing site in BC (Di Cicco et al., 2017); and between April 2011 and December 2013 through the DFO Regulatory Fish Health Audit Program on marine sites in BC, including in the Discovery Islands area (Laurin et al., 2019). Finally, on-going investigations examining PRV prevalence on thirteen Atlantic Salmon farms in BC detected PRV infections on

Atlantic Salmon farms in the Discovery Islands area throughout the year (unpublished data reported in Polinski and Garver (2019)).

Given that fish are transferred to marine rearing sites in the Discovery Islands area throughout the year (Appendix A, Figure 7), sites in this area could theoretically become positive throughout the year. While the sample sizes used are small, the results have been consistent throughout farms sampled in BC.

Overall, PRV has been reported on at least one Atlantic Salmon farm in the Discovery Islands area in all months of the year.

3.3.2.4 PRV survival in the marine environment

No studies have been conducted on the survival of PRV in the environment (Polinski and Garver, 2019). However, given that waterborne transmission of PRV has been demonstrated in seawater (Garver et al., 2016a; Polinski et al., 2019), it can be presumed that it maintains a capacity to survive in water even if the duration of survival and infectivity in seawater are unknown (Polinski and Garver, 2019). Additionally, being free of an envelope, PRV could be expected to have greater stability than, for example, the envelope containing aquatic virus infectious hematopoietic necrosis virus (Polinski and Garver, 2019).

3.3.2.5 Concurrence between Fraser River Sockeye Salmon and PRV

3.3.2.5.1 Spatial

Given evidence of juvenile and adult Fraser River Sockeye Salmon migration through the Discovery Islands area and evidence of PRV on at least one Atlantic Salmon farm in the Discovery Islands area, it was concluded that there is potential spatial concurrence between Fraser River Sockeye Salmon and PRV attributable to Atlantic Salmon farms in the Discovery Islands area.

3.3.2.5.2 Temporal

Table 10 summarizes evidence of temporal overlap between Fraser River Sockeye Salmon and PRV on Atlantic Salmon farms in the Discovery Islands area. Given that (1) Fraser River Sockeye Salmon are present in the Discovery Islands area between May and October; (2) Atlantic Salmon farms in the Discovery Islands area are stocked throughout the year; and (3) PRV has been reported throughout the year on Atlantic Salmon farms in the Discovery Island area, it was concluded that there is temporal concurrence between Fraser River Sockeye Salmon and PRV attributable to Atlantic Salmon farms in the Discovery Islands area.

Table 10. Summary of evidence of temporal overlap between Fraser River Sockeye Salmon and piscine orthoreovirus on Atlantic Salmon farms in the Discovery Islands area.The "X" indicates evidence of presence of Fraser River Sockeye Salmon in a given month; letters on the first row of the table represent months of the year from January to December. Data source: Marty et al. (2015); Di Cicco et al. (2017); Grant et al. (2018); Laurin et al. (2019) and unpublished data reported in Polinski and Garver (2019).

Fraser River Sockeye Salmon in the Discovery Islands area	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Lake-type juveniles					X	X	X					
Adults						X	X	X	X	X		
Farmed Atlantic Salmon in the Discovery Islands area	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Stocked net pens	X	X	X	X	X	X	X	X	X	X	X	X
Stocking events	X	X	X	X	X	X	X	X	X	X	X	X
PRV positive detections	X	X	X	X	X	X	X	X	X	X	X	X

3.3.3 Assumptions

- PRV has been released from at least one Atlantic Salmon farm in the Discovery Islands area;
- Positive detections of PRV is evidence that the pathogen is present in sampled fish;
- PRV-infected fish are shedding the virus;
- Shedding occurs during months with evidence of infection on farms;
- Pacific salmon can use all channels in the Discovery Islands area; and
- Wild Sockeye Salmon and Sockeye Salmon produced through enhancement are not differentiated for the purpose of this risk assessment.

3.3.4 Likelihood of exposure

Table 11 presents the main factors contributing to and limiting the likelihood of Fraser River Sockeye Salmon to be exposed to PRV attributable to Atlantic Salmon farm(s) in the Discovery Islands area. Those factors were used to determine the likelihood and uncertainty rankings based on definitions in Tables 2, 5 and 6.

Table 11. Factors contributing to and limiting the likelihood that at least one Fraser River Sockeye Salmon would be exposed to piscine orthoreovirus-1 released from infected Atlantic Salmon farm(s) in the Discovery Islands area under the current farm practices.

Contributing factors	Limiting factors
• Juvenile and adult Fraser River Sockeye Salmon migrate through the Discovery Islands area every year; • All Atlantic Salmon farms in the Discovery Islands area are anticipated to become infected with PRV within 100-200 days post-seawater transfer; and • There is temporal overlap between Fraser River Sockeye Salmon migration (May through October) and the presence of PRV on Atlantic Salmon farms in the Discovery Islands area.	• Atlantic Salmon farms are not found in all channels of the Discovery Islands area; and • Atlantic Salmon farms occupy a very small surface area and volume of the Discovery Islands area and width of channels.

Two exposure groups were assessed: (1) juvenile Fraser River Sockeye Salmon; and (2) adult Fraser River Sockeye Salmon. Waterborne exposure is considered as the most relevant exposure route for Fraser River Sockeye Salmon in the context of this risk assessment.

3.3.4.1 Exposure of juvenile Fraser River Sockeye Salmon

It was concluded that the likelihood of at least one juvenile Fraser River Sockeye Salmon to be exposed to PRV attributable to Atlantic Salmon farms located in the Discovery Islands area through waterborne exposure is **extremely likely** under the current farm practices given the temporal overlap with reports of PRV on farms. This conclusion was made with **reasonable certainty** given abundant and robust data documenting the presence of juvenile Sockeye Salmon in the Discovery Islands area but lack of knowledge on the spatial and temporal distribution in proximity to farms and PRV survival in the marine environment.

3.3.4.2 Exposure of adult Fraser River Sockeye Salmon

It was concluded that the likelihood of at least one adult Fraser River Sockeye Salmon to be exposed to PRV attributable to an Atlantic Salmon farm located in the Discovery Islands area through waterborne exposure is **extremely likely** under the current farm practices given the temporal overlap with reports of PRV on farms. This conclusion was made with **reasonable certainty** given abundant and robust data documenting the presence of adult Sockeye Salmon in the Discovery Islands area but lack of knowledge on the spatial and temporal distribution in proximity to farms and PRV survival in the marine environment.

3.4 INFECTION ASSESSMENT

3.4.1 Question

Assuming that at least one Fraser River Sockeye Salmon has been exposed to PRV released from Atlantic Salmon farms in the Discovery Islands area, what is the likelihood that at least one will become infected?

3.4.2 Considerations

The infection assessment consists of determining the likelihood that Fraser River Sockeye Salmon will be exposed to PRV at a concentration and for a duration sufficient to cause infection.

Considerations include Sockeye Salmon susceptibility to PRV infection; PRV infection dynamics; oceanographic and environmental conditions; PRV minimum infectious dose; estimated PRV waterborne concentration attributable to Atlantic Salmon farms; hydrodynamic dispersal; and estimated potential duration of exposure.

3.4.2.1 Sockeye Salmon susceptibility to PRV infection

Sockeye Salmon susceptibility to PRV infection is demonstrated by the following cohabitation study and detections reported in Sockeye Salmon sampled in the field.

PRV negative Atlantic and Sockeye salmon sentinels cohabitated with western North American PRV positive Atlantic Salmon donors became infected with the virus after four weeks of cohabitation in seawater (Garver et al., 2016a) providing evidence of Sockeye Salmon susceptibility to PRV infection. Other studies also reported PRV infections in Sockeye Salmon but through intraperitoneal injections (Garver et al., 2016b; Polinski et al., 2016) which do not mimic natural transmission pathways.

Sockeye Salmon appears to be less susceptible to PRV infections than Atlantic Salmon given lower prevalence and viral load and given that infections appear to take longer to develop (Garver et al., 2016a; Polinski and Garver, 2019). For instance, based on a cohabitation study with PRV-infected Atlantic Salmon, 40% (4/10) of Sockeye Salmon sentinels compared to 100% (15/15) of Atlantic Salmon sentinels became infected with PRV after four weeks of cohabitation (Garver et al., 2016a). Additionally, PRV viral load peaked in 12 weeks in Sockeye Salmon sentinels compared to six weeks in Atlantic Salmon sentinels, and maximum viral loads remained lower in blood and kidney in Sockeye Salmon sentinels compared to Atlantic Salmon sentinels (Garver et al., 2016a). Finally, some Sockeye Salmon appeared to be refractory to PRV infection or were able to clear the infection (Garver et al., 2016a).

PRV genetic material has also been detected in Fraser River Sockeye Salmon sampled in BC waters (Jeffries et al., 2014; Miller et al., 2014; Marty et al., 2015; Furey, 2016; Morton et al., 2017; Teffer et al., 2017; Nekouei et al., 2018; Stevenson, 2018).

3.4.2.2 Infection dynamics of PRV

Polinski and Garver (2019) summarized the dynamics of PRV infections as observed in Atlantic Salmon in three main phases: (1) early entry and dissemination; (2) peak systemic replication; and (3) long-term persistence.

During the early entry and dissemination phase, which typically lasts two to three weeks at 12°C, the virus enters the host, replicates and disseminates into blood cells. The virus is not likely being shed into the environment to a high degree during this phase (Polinski et al., 2019).

During the peak systemic replication phase, which typically lasts two to three weeks at 12°C, substantial PRV replication takes place within erythrocytes (Finstad et al., 2014; Wessel et al., 2015; Haatveit et al., 2017; Polinski and Garver, 2019) leading to the highest systemic blood loads of PRV.

During the long-term persistence phase there is a reduction in viral protein production but large quantities of genomic PRV material remain associated with the erythrocyte cell fraction

(Haatveit et al., 2017; Lund et al., 2017; Polinski et al., 2019). Shedding of the virus is minimal during this phase and may even cease entirely over time (Garver et al., 2016a).

3.4.2.3 Oceanographic and environmental conditions

Water temperatures in the Discovery Islands area vary both seasonally and regionally with recorded temperatures ranging between 3 and 24°C (Chandler et al., 2017). Monthly water temperature in the top 15 m of Atlantic Salmon farms in the Discovery Islands area ranges from 7.6 ± 2.3°C to 11.5 ± 3.3°C (mean ± std) (Chandler et al., 2017).

Water salinity in the Discovery Islands area varies considerably by season (due to river runoff of snowmelt), by depth (due to the estuarine circulation), and by location (as some narrow channels are extremely well mixed vertically) ranging from close to zero to 32. Monthly salinity in the top 15 m of Atlantic Salmon farms in the Discovery Islands area ranges from 28.9 ± 7.3 to 29.9 ± 8.7 (mean ± std) (Chandler et al., 2017).

Whether salinity or temperature influences the survival of PRV in the marine environment is not known. However, the transmission of PRV to Atlantic Salmon in the Discovery Islands area demonstrates that the oceanographic and environmental conditions are conducive for transmission.

3.4.2.4 PRV minimum infectious dose

No studies have attempted to determine the minimum dose required to infect Sockeye Salmon with PRV.

In Atlantic Salmon, preliminary evidence using PRV from Pacific Canada suggests that $\leq 10^3$ PRV particles are sufficient to initiate infection by intra-peritoneal injection (Polinski, unpublished data reported in Polinski and Garver (2019)). However, injections are not representative of natural exposure and consequently the amount of PRV known to cause infection by injection cannot be extrapolated to a more environmental relevant exposure route.

In Pink Salmon (*O. gorbuscha*), bath exposures to 1,000 purified PRV particles per mL for one hour failed to infect 1 g fish (n=20) in seawater up to six weeks after exposure (Richard, Polinski, and Garver, unpublished data reported in Polinski and Garver (2019)), providing a better representation of a natural exposure route.

The minimum dose required to induce PRV infection by immersion or ingestion in Sockeye Salmon remains unknown, but is likely dependent upon the route of virus exposure, host condition, stock, and species (Polinski and Garver, 2019).

3.4.2.5 Estimated PRV waterborne concentration attributable to Atlantic Salmon farms

Quantifying the infection pressure from an infected farm requires estimations of the number of infected fish on farm, the shedding rate in infected-fish and the volume of the farm.

Although the average volume of Atlantic Salmon farms in the Discovery Islands area has been estimated to be approximately 195,000 m^3 (Mimeault et al., 2017) and that PRV prevalence on an infected Atlantic Salmon farm can be expected to reach 100% at some point within the production cycle (see Exposure Assessment), the viral shedding rate in PRV-infected Atlantic Salmon (or other salmonids) has not been quantified (Polinski and Garver, 2019). Consequently, it is not possible to estimate the infection pressure from a PRV-infected Atlantic Salmon farm in the Discovery Islands area.

3.4.2.6 Hydrodynamic dispersal

Modelling the hydrodynamic dispersion of a pathogen in the marine environment requires an ocean and circulation model, the infection pressure attributable to the source and information about the survival of the pathogen in the marine environment.

There is an existing ocean and circulation model available for the Discovery Islands area (Foreman et al., 2012) that has been used to model hydrodynamic dispersion of infectious hematopoietic necrosis virus (IHNV) between farms (Foreman et al., 2015a) and dispersion of IHNV (Mimeault et al., 2017) and *Aeromonas salmonicida* (Mimeault et al., 2019a) in the Discovery Islands area.

Nevertheless, it was not possible to model the dispersal of PRV from infected Atlantic Salmon farms in the Discovery Islands area for this risk assessment given that the viral infection pressure attributable to a PRV-infected farm cannot be estimated (see section on Estimated PRV concentration attributable to Atlantic Salmon farms) and there are no data on the survival (or decay rate) of PRV in the marine environment (Polinski and Garver, 2019).

3.4.2.7 Estimated duration of exposure

The potential duration that Fraser River Sockeye Salmon could be exposed to PRV released from an Atlantic Salmon farm in the Discovery Islands area depends on the time Fraser River Sockeye Salmon spend in the Discovery Islands area in proximity of infected farm(s) and the time an infected farm remains infectious.

3.4.2.7.1 Duration of PRV infections on Atlantic Salmon farms

Once infected, the on-going persistence of PRV infections in Atlantic Salmon has been demonstrated over 59 weeks under experimental conditions (Garver et al., 2016a) and five months under field conditions (Di Cicco et al., 2017). Horizontal transmission of PRV has been hypothesized to primarily occur between 3 to 15 weeks following infection, after which the potential for natural shedding would become severely reduced (Polinski and Garver, 2019).

3.4.2.7.2 Residence time of Fraser River Sockeye Salmon in Discovery Islands area

Grant et al. (2018) estimated the residence time of juvenile and adult Sockeye Salmon in the Discovery Islands area, from which Mimeault et al. (2017) estimated, assuming a constant migration speed and unidirectional movement, that juveniles could encounter farms over three to eight days while returning adults could encounter farms over two days during their migration through the Discovery Islands area.

3.4.2.7.3 Fraser River Sockeye Salmon in proximity to Atlantic Salmon farms

In a recent telemetry study, the median travel time of juvenile Fraser River Sockeye Salmon through Hoskyn and Okisollo channels was approximately 30 hours and travel time from the eastern to the western end of the Okisollo Channel was approximately six hours (sample size unspecified) (Rechisky et al., 2018).

In the same study, the median time juvenile Sockeye Salmon spent near two fallowed salmon farms was approximately 4.5 minutes suggesting short exposure time to fallowed farms (Rechisky et al., 2018).

3.4.3 Assumptions

- At least one Fraser River Sockeye Salmon has been exposed to PRV released from Atlantic Salmon farms in the Discovery Islands area;

- All Fraser River Sockeye Salmon are assumed to be equally susceptible to PRV regardless of life stage or stock of origin;
- Juvenile and adults Fraser River Sockeye Salmon are considered naïve to PRV when migrating through the Discovery Islands area; and
- PRV is dispersed throughout the Discovery Islands area from infected Atlantic Salmon farms.

3.4.4 Likelihood of infection

Table 12 presents the main factors contributing and limiting the likelihood that Fraser River Sockeye Salmon would become infected with PRV released from Atlantic Salmon farm(s) located in the Discovery Islands area. Those factors were used to determine likelihood and uncertainty rankings based on definitions in Tables 2, 5 and 6.

Table 12. Factors contributing to and limiting the likelihood that at least one Fraser River Sockeye Salmon will become infected with piscine orthoreovirus-1 released from infected Atlantic Salmon farms in the Discovery Islands area under current farm practices.

Contributing factors	Limiting factors
• Sockeye Salmon are susceptible to PRV infection; • Based on juvenile swimming speed and distance it is estimated that juvenile Sockeye Salmon could encounter Atlantic Salmon farms over three to eight days during their migration through the Discovery Islands area; • It is estimated that returning adult Sockeye Salmon could encounter Atlantic Salmon farms over two days during their migration through the Discovery Islands area; • All Atlantic Salmon farms in the Discovery Islands area are anticipated to become infected with PRV within 100-200 days post-seawater transfer; and • PRV prevalence in farmed Atlantic Salmon in the marine environment is expected to reach 100% approximately 200-300 days post seawater transfer.	• Based on a telemetry tracking study, juvenile Sockeye Salmon spend limited time (minutes) in the vicinity of fallowed farms; • Median travel time of juvenile Fraser River Sockeye Salmon from Hoskyn Channel to Okisollo Channel (25 km) was estimated to be approximately 30 hours; and within Okisollo Channel, travel time from the eastern end to the western end (4 km) was approximately six hours; • Based on laboratory studies, PRV-infected Atlantic Salmon appear to be most contagious between 3 and 15 weeks following PRV infection, after which the potential for horizontal transmission is severely reduced; and • Sockeye Salmon appear to be less susceptible to PRV infections than Atlantic Salmon given lower prevalence and viral load and given that infections appear to take longer to develop.

Likelihood of infection was considered for two exposure groups: (1) juvenile Fraser River Sockeye Salmon; (2) adult Fraser River Sockeye Salmon.

It was concluded that the likelihood of at least one Fraser River Sockeye Salmon, at either the juvenile or adult life stage, to become infected with PRV attributable to Atlantic Salmon farms in the Discovery Islands area through waterborne exposure under the current farm practices is **very likely** given that Sockeye Salmon are susceptible to PRV infection and have been shown to become infected in cohabitation studies. This conclusion was made with **high uncertainty** given incomplete data and given that opinions of the authors of this risk assessment varied.

Whether exposure to PRV at environmentally relevant concentrations around the farms and for the period of time that Fraser River Sockeye Salmon migrate through the Discovery Islands area where farms are present (three to eight days for juveniles, two days for adults) will result in infection in Sockeye Salmon is not known. This ranking is based on an unrealistic assumption of constant high level of PRV shedding from infected farms and hence represents a worst case scenario (Garver et al., 2016a; Polinski et al., 2019).

3.5 OVERALL LIKELIHOOD ASSESSMENT

The estimated likelihoods were combined as per the combination rules described in the methodology section. The combined likelihood for the release assessment was determined by adopting the highest likelihood ranking among the release pathways. The combined likelihood for each exposure group was determined by adopting the lowest ranking among the farm infection, release, exposure and infection assessments.

Table 13 summarizes the likelihood assessment. Overall, it was concluded that the likelihood that at least one Fraser River Sockeye Salmon would become infected with PRV released from Atlantic Salmon farms in the Discovery Islands area is **very likely** for both exposure groups. This conclusion is driven by the likelihood of infection which is highly uncertain given the lack of data about PRV shedding rates from PRV-infected Atlantic Salmon and the minimum dose of PRV required to infect Sockeye Salmon.

Table 13. Summary of the likelihood rankings and uncertainty levels for the likelihood assessment of the piscine orthoreovirus-1 risk assessment.Descriptions of the uncertainties can be found with each likelihood assessment steps; uncertainties are not combined. Estimates are reported in white cells and likelihood combination results are reported shadowed cells under the "Rankings" column.

Steps		**Rankings**	
Farm infection assessment	**Likelihood of farm infection**	Extremely likely *(high certainty)*	
Release assessment	**Release pathways**	**Farmed Atlantic Salmon**	**Vectors and fomites**
	Likelihood of release	Extremely likely *(high certainty)*	Unlikely *(reasonable uncertainty)*
	Combined likelihoods of release	Extremely likely	
Exposure and infection assessments	**Exposure groups**	**At least one juvenile Fraser River Sockeye Salmon**	**At least one adult Fraser River Sockeye Salmon**
	Likelihood of exposure	Extremely likely *(reasonable certainty)*	Extremely likely *(reasonable certainty)*
	Likelihood of infection	Very likely *(high uncertainty)*	
Combined exposure and infection likelihoods for each exposure group		Very likely	Very likely
Combined likelihoods (farm infection, release, exposure and infection) for each exposure group		Very likely	Very likely

4 CONSEQUENCE ASSESSMENT

The consequence assessment aims to determine the potential magnitude of impacts of PRV attributable to Atlantic Salmon farms in the Discovery Islands area on the abundance and diversity of the Fraser River Sockeye Salmon.

Based on the likelihood assessment, it was determined that it is very likely that at least one Fraser River Sockeye Salmon would become infected with PRV released from Atlantic Salmon farms in the Discovery Islands area given that all farms could become infected with PRV after seawater transfer of Atlantic Salmon, that PRV infections could happen at any month of the year, and that infections can persist and given Sockeye Salmon susceptibility to PRV infection.

Assuming that at least one Fraser River Sockeye Salmon would have been infected with PRV attributable to infected Atlantic Salmon farms, the consequence assessment explores the potential magnitude of impacts to the number of returning adults and diversity of Fraser River Sockeye Salmon.

4.1 QUESTION

Assuming that at least one susceptible Fraser River Sockeye Salmon has been infected with PRV released from infected Atlantic Salmon, what is the potential magnitude of impact on the number of returning adults and diversity of Fraser River Sockeye Salmon?

4.2 CONSIDERATIONS

Considerations include pathogenicity and virulence of PRV; PRV prevalence in Sockeye Salmon; and proportion of Fraser River Sockeye Salmon exposed to infected farms in the Discovery Islands area.

4.2.1 Pathogenicity and virulence of PRV

To date, PRV-1 is the only genogroup detected in North America (Polinski and Garver, 2019) hence the focus of this risk assessment. Refer to Polinski and Garver (2019) for a summary of the state of knowledge related to the pathogenicity of other PRV genogroups in different salmonid species and regions.

Briefly, PRV-1 has been demonstrated to be an etiological component of heart and skeletal muscle inflammation (HSMI) in farmed Atlantic Salmon in Norway (Wessel et al., 2017) and is a putative contributing factor in severe cardiomyopathy in farmed Atlantic Salmon in Pacific Canada (Di Cicco et al., 2017; Di Cicco et al., 2018). PRV-1 has also been suggested to be a contributing factor in jaundice/anemia in farmed Chinook Salmon (*O. tshawytscha*) in Pacific Canada (Di Cicco et al., 2018).

However, under experimental conditions with Atlantic Salmon, PRV from Pacific Canada was highly infectious but did not cause HSMI (Garver et al., 2016a), did not result in impaired respiratory function (Zhang et al., 2019) and was of low virulence causing only minor focal heart inflammation without significant transcriptional induction of immune genes (Polinski et al., 2019).

4.2.1.1 Farmed Atlantic Salmon

In Norway, most farmed Atlantic Salmon become PRV positive but only some develop disease (Polinski and Garver, 2019). While HSMI is common in farmed Atlantic Salmon in Norway (Kongtorp et al., 2004a; Kongtorp et al., 2004b; Kongtorp et al., 2006; Palacios et al., 2010), it is not clear why some experience high losses and others do not (Polinski and Garver, 2019).

In contrast, while most farmed Atlantic Salmon in Pacific Canada also become PRV positive, clinical HSMI outbreaks as in Norway have not been reported (Polinski and Garver, 2019) but subclinical farm-level cases of HSMI-like disease have been suggested for which PRV may or may not be a causative factor (Di Cicco et al., 2017; Di Cicco et al., 2018; Polinski et al., 2019).

No fish health events nor mortality events have been attributed to HSMI on Atlantic Salmon farms in BC.

4.2.1.2 Sockeye Salmon

Of most relevance to this risk assessment are the consequences of PRV infection in Sockeye Salmon. To date, there is no evidence that PRV causes disease in Sockeye Salmon despite successful infection with the virus under experimental conditions (Garver et al., 2016a; Garver et al., 2016b; Polinski et al., 2016).

Sockeye Salmon post-smolts (40 g) challenged by intraperitoneal injections with a PRV inoculum prepared from infectious Atlantic Salmon developed considerable blood and kidney PRV loads but no weight loss, morbidity or pathology could be attributed to the virus over 62 days after challenge (Polinski et al., 2016). Despite high viral loads, PRV only induced a weak host response in head kidneys within the first three to four weeks of infection and the presence of PRV did not change the host response to a superinfection with infectious hematopoietic necrosis virus (Polinski et al., 2016).

In another laboratory study, PRV negative Atlantic and Sockeye salmon (sentinels) were cohabitated in seawater with PRV positive Atlantic Salmon (75 g) (donors) injected with an inoculum prepared from highly PRV infective Atlantic Salmon. Despite high prevalence and persistence of PRV in blood and kidney of both sentinel species over 59 weeks, no microscopic lesions, disease or mortality could be attributed to the virus (Garver et al., 2016a).

Chinook Salmon, Sockeye Salmon and Atlantic Salmon challenged by intraperitoneal injections with a PRV inoculum prepared from jaundiced Chinook Salmon did not develop clinical jaundice despite testing positive for PRV five months after challenge (Garver et al., 2016b).

Finally, preliminary data indicate that PRV infections are inconsequential to Sockeye Salmon respiratory function (reported in Polinski and Garver (2019)).

The results from the above laboratory studies suggest that PRV from Pacific Canada is infectious but of low virulence to Sockeye Salmon (Garver et al., 2016a; Polinski et al., 2016; Polinski and Garver, 2019). Additionally, the presence of PRV on or in the gills had no significant effects on the likelihood that returning adult Fraser River Sockeye Salmon from Chilko or Shuswap Lake stocks would reach their spawning grounds (Miller et al., 2014). Overall, current evidence does not support the conclusion that BC PRV-1 causes disease or mortality in Sockeye Salmon.

4.2.2 PRV prevalence in Sockeye Salmon

Polinski and Garver (2019) summarized PRV screening results in Pacific Salmon sampled from Alaska, British Columbia and Washington from which they estimated an overall PRV prevalence of 1.4% in Sockeye Salmon based on results from 12 independent studies. PRV prevalence were estimated based on results aggregated at face value for positive and negative detections while understanding that there are no reported test performance characteristics for the various studies and that they differ in sampling protocols, analytical techniques and quality control stringencies (Polinski and Garver, 2019).

Table 14 summarises the PRV screening and positive detection in Sockeye Salmon per life stage and environment. Of the 6693 Sockeye Salmon screened for PRV, 4725 have been attributed to the Fraser River. With a total of 86 positive detections in Fraser River Sockeye Salmon, the overall PRV prevalence in Fraser River Sockeye Salmon is estimated to be 1.8%. Most positive detections were reported in returning adults (83/86) with respective PRV prevalence of 0.1% and 4.2% in juveniles and adults Fraser River Sockeye Salmon.

PRV prevalence in juvenile Fraser River Sockeye Salmon is similar in freshwater (0.1%) and seawater (0.2%) while in returning adults PRV prevalence in freshwater (1.3%) is lower than in seawater (12.1%) (Table 14). However, 98% (63/64) of positive detections in returning adult Fraser River Sockeye Salmon sampled in seawater were from gill biopsies and might not all be indicative of systemic infections as liver samples taken at the time of gill biopsies, as well as subsequently in the Fraser River, were negative (Polinski and Garver, 2019).

Table 14. Percent PRV positive detections in Sockeye Salmon summarized by life stage and sampling environment. Panel A includes results from all Sockeye Salmon screened for PRV, including Fraser River Sockeye Salmon, while Panel B only includes results for Fraser River Sockeye Salmon. Numbers in parentheses are the number of fish that tested positive for PRV over the number of fish screened for PRV. Adapted from Polinski and Garver (2019) which includes results aggregated/summarized PRV results at face value for positive and negative detection without comparisons across the following studies: Jeffries et al. (2014); Miller et al. (2014); Marty et al. (2015); Furey (2016); Morton et al. (2017); Teffer et al. (2017); Nekouei et al. (2018); Purcell et al. (2018); Stevenson (2018); Thakur et al. (2019); Hrushowy (2018); and Johnson (unpublished).

(A) Sockeye Salmon from Alaska, British Columbia (including Fraser River) and Washington

Fry	**Juveniles**		**Adults**		**Total**
Freshwater	Freshwater	Seawater	Seawater	Freshwater	
3.4% (3/89)	**0.1%** (1/1879)	**0.4%** (8/1943)	**11.4%** (64/560)	**0.9%** (21/2222)	**1.4%** (97/6693)
3.4% (3/89)	**0.2%** (9/3822)		**2.9%** (85/2912)		

(B) Fraser River Sockeye Salmon only

Juveniles		**Adults**		**Total**
Freshwater	Seawater	Seawater	Freshwater	
0.1% (1/1505)	**0.2%** (2/1258)	**12.1%** (64/531)	**1.3%** (19/1431)	**1.8%** (86/4725)
0.1% (3/2763)		**4.2%** (83/1962)		

Polinski and Garver (2019) also summarized PRV screening results by Fraser River Sockeye Salmon stocks. To date, of the 4725 Fraser River Sockeye Salmon screened for PRV, 4337 have been genetically attributed to specific stocks from the Fraser River, including 22 of the 24 Fraser River Sockeye Salmon conservation units (CUs) (Table 15).

Positive detections have been reported in six Fraser River Sockeye Salmon stocks (Adams, Chilko Lake, Cultus Lake, Nadina River, Stuart Lake and Shuswap Lake) representing five to seven of the 24 conservation units. Given the low sample size of fish screened for PRV in some stocks and absence of screening for PRV in other stocks, PRV may also be present in other stocks and conservation units.

Caution should be applied at comparing proportion of Fraser River Sockeye Salmon positive for PRV across CUs and at inferring differences in susceptibility as PRV screening results were aggregated without comparisons across studies. Additionally, most (63/64) of the PRV positive detections reported in returning adult Fraser River Sockeye Salmon sampled in seawater were from gill biopsies (Miller et al., 2014) while liver samples taken at the same time as gill biopsies as well as subsequently in the Fraser River were negative for PRV; suggesting that the PRV on or in the gill tissues of these fish did not represent systemic infections nor did systemic infections likely develop before returning fish reached their spawning grounds (Polinski and Garver, 2019).

*Table 15. Distribution of PRV detection across Fraser River Sockeye Salmon stocks and the 24 Wild Salmon Policy Conservation Units.Sources: 2017 integrated biological status as per DFO (2018a). PRV screening results as per Jeffries et al. (2014); Miller et al. (2014); Marty et al. (2015); Furey (2016); Morton et al. (2017); Teffer et al. (2017); Nekouei et al. (2018); Stevenson (2018). EStu: Early Stuart; ES: Early Summer; S: Summer; L: Late; NA; Not applicable, --: no tests, * questionnable positive detection in Marty et al. (2015), GB includes gill biopsies.*

2017 status		Conservation unit-Management unit	Stock screened for PRV	PRV screening results	
				Juveniles	Adults
Red		Bowron-ES	Bowron	0/9	--
Red		Cultus-L	Cultus	1/62	--
Red		Taseko-ES	--	--	--
Red		Widgeon-River	--	--	--
Red		Harrison (U/S)-L	Weaver	0/8	--
Red		Seton-L	Portage	0/35	--
Red		Takla-Trembleur-EStu	Early Stuart, Late Stuart & Misc.[1]	0/4	1/191
R	A	Takla-Trembleur-Stuart-S			
R	A	Quesnel-S	Quesnel	0/22	0/297
			Horsefly	0/148	--
			Mitchell	0/119	--
			Blue Lead	0/1	--
			Wasko-Roaring	0/16	--
Amber		Nahatlatch-ES	Nahatlatch River	0/16	--
Amber		North Barriere-ES	Fennell	0/1	--
Amber		Kamloops-ES	Thompson	0/75	--
			Raft	0/18	--
			Upper Barrier	0/3	--
Amber		Lillooet-Harrison-L	Birkenhead	0/77	0/11
Amber		Shuswap-ES	Scotch[2]	0/72	0/8
			Seymour[2]	0/134	--
A	G	Shuswap Complex-L	Adams	1/370	0/2
			Shuswap[3]	0/398	49[GB]/304
			Eagle	0/6	--
			Little	0/5	--
A	G	Nadina-Francois-ES	Nadina	0/60	1[4]/60
A	G	Chilliwack-ES	Dolly Varden	0/86	--
			Chilliwack Lake	0/34	--
A	G	Francois-Fraser-S	Stellako	0/137	0/10
A	G	Anderson-Seton-ES	Gates	0/65	0/19
A	G	Harrison (D/S)-L	Big Silver	0/4	--
Green		Pitt-ES	Pitt	0/79	--
Green		Harrison River - River	Harrison[5]	--	0/103
Green		Chilko-S and Chilko-ES	Chilko[6]	0/1018	15[GB]/250
DD		Chilko-ES			
Sub-total by life stage				2/3082 (0.1%)	66/1255 (5.3%)
Total				68/4337 (1.6%)	

[1] We are unable to distinguish whether samples identified as belonging to the Stuart stock are part of the "Takla-Trembleur-EStu" CU or the "Takla-Trembleur-Stuart-S" CU. We also include juvenile fish sampled from Sandpoint Creek, Five Mile Creek, Middle River, and Dist-Sinta Creek (n=1 per stock) as part of this combined TTE or TTS CU.

[2] We have assumed that samples identified as belonging to Scotch Creek and Seymour River are from the early summer timed CU "Shuswap-ES"; however, we note that both of these streams also produce a smaller late-timed run that is part of the "Shuswap Complex-L" CU.

[3] We have included stocks from the Middle Shuswap River (n=53) in this categorization, although it is possible that some of these fish may be of the Shuswap-ES CU.

[4] Positive detection of PRV nucleic acid in only one of two technical replicates which was noted as inconclusive by the authors (Marty et al., 2015).

[5] We have assumed that adult samples identified as belonging to the Harrison stock are part of the "Harrison River – River" CU.

[6] We are unable to distinguish whether samples identified as belonging to the Chilko stock are part of the "Chilko-S" CU or the "Chilko-ES" CU.

4.2.3 Proportion of Fraser River Sockeye Salmon exposed to infected farms

This section explores the proportion of Fraser River Sockeye Salmon population that could potentially be exposed to PRV attributable to an infected Atlantic Salmon farm in the Discovery Islands area. These estimations are based on the timing of Fraser River Sockeye Salmon migration and evidence of infections on farms in the area.

For both juveniles and adults, despite evidence of PRV detections on farms in every month, it should be noted that Atlantic Salmon farms are not located in every channels and do not occupy a large volume of the Discovery Islands area (Mimeault et al., 2017) and consequently, it is reasonable to assume that not all Fraser River Sockeye Salmon would encounter an infected farm or be exposed to pathogens dispersed from infected farm(s).

4.2.3.1 Juvenile

Knowledge of juvenile marine out-migration routes through the Discovery Islands area and interactions with Atlantic Salmon farms is limited. Consequently, it is not possible to estimate the proportion of the population that could swim by a PRV-infected Atlantic Salmon farm. It was therefore assumed that all out-migrating juvenile Fraser River Sockeye Salmon could potentially be exposed to PRV attributable to infected farm(s) during their migration through the Discovery Islands area. This assumption should be reviewed as our knowledge of Fraser River Sockeye Salmon migratory routes expands.

4.2.3.2 Adults

Sockeye Salmon return to the Fraser River either through the northern route (Johnstone Strait) or the southern route (Strait of Juan de Fuca) (reviewed in Grant et al. (2018)). Northern diversion rates are highly variable with rates ranging from 10% to 96% annually between 1980 and 2015 (Pacific Salmon Commission data presented in Grant et al. (2018)). Assuming that all returning Sockeye Salmon using the northern route would migrate through the Discovery Islands area, between 10 and 96% of returning adult Fraser River Sockeye Salmon could be exposed to an Atlantic Salmon farm during their migration.

4.3 ASSUMPTIONS

- Results from laboratory studies on the impact of PRV infection in Sockeye Salmon are indicative of what occurs in the marine environment;
- Prevalence of PRV in samples is representative of the prevalence of the whole stock in all years;
- Juvenile and adult Fraser River Sockeye Salmon are assumed to be equally susceptible to PRV; and
- All Fraser River Sockeye Salmon stock have the same susceptibility.

4.4 MAGNITUDE OF CONSEQUENCES

The consequence assessment explores the potential magnitude of impact to the abundance and diversity of Fraser River Sockeye Salmon resulting from juvenile and adult Fraser River Sockeye Salmon infected with PRV released from Atlantic Salmon from all farms located in the Discovery Islands area. Effects, if any, would be limited to the fish infected with PRV attributable to Atlantic Salmon farms in the Discovery Islands area.

The potential magnitude of consequences on both the abundance and diversity of Fraser River Sockeye Salmon resulting from infection with PRV attributable to Atlantic Salmon farms in the Discovery Islands area was determined for juvenile and adult Fraser River Sockeye Salmon. Rankings were determined referring to definitions of consequence to abundance (Table 3), consequences to diversity (Table 4) and uncertainty (Table 5).

4.4.1 Juvenile Fraser River Sockeye Salmon

Lake-type juvenile Fraser River Sockeye Salmon migrate through the Discovery Islands area during their outmigration towards the ocean. Given the ubiquitous nature of PRV on Atlantic Salmon farms and its high prevalence and persistence on infected farms, it was concluded that it is very likely that at least one juvenile Fraser River Sockeye Salmon would become infected during their outmigration. However, it is not possible to determine the proportion of the juveniles that could become infected nor the potential for an infection acquired in the Discovery Islands area to spread to other juvenile Fraser River Sockeye Salmon during migration at sea.

However, although the proportion of juvenile Fraser River Sockeye Salmon getting infected with PRV attributable to Atlantic Salmon farms is unknown, only two positive PRV detections have been reported in juvenile Fraser River Sockeye Salmon sampled in seawater over a total of 1258 (0.2%) (Polinski and Garver, 2019) (Table 14). Whether this low prevalence in juveniles sampled at sea is an artefact of the short time period between potential infection and screening is unknown but is a possibility as Garver et al. (2016a) demonstrated that several weeks post exposure are necessary for detection of the virus in both Atlantic and Sockeye salmon under experimental conditions. Regardless of the proportion infected, PRV from Pacific Canada appears to be infectious but of low virulence under laboratory conditions (Garver et al., 2016a; Garver et al., 2016b; Polinski et al., 2016; Polinski and Garver, 2019).

Overall, the low virulence, absence of impact on respiratory performance of PRV in juvenile Sockeye Salmon suggest a limited impact of PRV on the survival of Fraser River Sockeye Salmon. It was therefore concluded that the potential magnitude of consequences to the abundance of Fraser River Sockeye Salmon would be **negligible**. This conclusion was made with **reasonable certainty** given abundant and robust data on the low prevalence and virulence of PRV in Sockeye Salmon.

Juvenile Fraser River Sockeye Salmon from 22 conservation units have been screened for PRV. Two PRV positive detections have been reported: one in the Cultus-L and one in the

Shuswap Complex-L conservation units. However, given the low virulence of the virus in juvenile Sockeye Salmon, it was concluded that the potential magnitude of consequences to the diversity of Fraser River Sockeye Salmon would be **negligible** over two generations (eight years). This conclusion was made with **reasonable certainty** given abundant and robust data on the low prevalence and virulence of PRV in Sockeye Salmon.

4.4.2 Adult Fraser River Sockeye Salmon

In any given year, between 10 and 96% of returning adult Fraser River Sockeye Salmon migrate through the northern diversion route (Grant et al., 2018) and hence could be exposed to an Atlantic Salmon farm in the Discovery Islands area. Given the ubiquitous nature of PRV on Atlantic Salmon farms and its high prevalence and persistence on infected farms, it was concluded that it is very likely that at least one adult Fraser River Sockeye Salmon would become infected during their migration through the Discovery Islands area. However, it is not possible to determine the proportion of adults that could become infected due to Atlantic Salmon farms in the Discovery Islands area.

Overall, the average PRV prevalence in adult Fraser River Sockeye Salmon is 4.2% with a maximum of 12.1% in seawater. However, most (63/64) of the PRV positive detections reported in returning adult Fraser River Sockeye Salmon sampled in seawater were from gill biopsies (Miller et al., 2014). Liver samples taken at the same time of gill biopsies as well as subsequently in the Fraser River were negative for PRV; suggesting that the PRV on or in the gill tissues of these fish did not represent systemic infections nor did systemic infections likely develop before returning fish reached their spawning grounds (Polinski and Garver, 2019).

Returning Fraser River Sockeye Salmon can travel the distance between the southeastern limit of the Discovery Islands area and Mission in approximately three to four days (Grant et al., 2018). The distance between Fraser River Sockeye Salmon spawning grounds and the ocean ranges widely, from 40 km for the Widgeon Slough population to 1,200 km for the Early Stuart population (Cohen, 2012b). Early Stuart River Sockeye Salmon took up to a month to reach their spawning grounds from the mouth of the Fraser River (Stoddard, 1993). Consequently, depending on the stocks, returning adults can take up to 35 days to reach their spawning grounds from the Discovery Islands area.

Given that under experimental conditions Sockeye Salmon required four weeks to develop detectable PRV infections through cohabitation with Atlantic Salmon donors (Garver et al., 2016a), that PRV transmission likely takes more than three weeks to occur following infection (Polinski and Garver, 2019) and that PRV prevalence in adult Fraser River Sockeye Salmon sampled in freshwater is 1.3%, no significant spread of infection within the returning adults prior to spawning is expected.

PRV infections had no significant effects on the likelihood that returning adult Fraser River Sockeye Salmon from two different stocks would reach their spawning grounds (Miller et al., 2014). In absence of additional data specific to PRV infections in adult Sockeye Salmon, surrogate data based on different species or different life stages were also considered:

- Notwithstanding that PRV responses vary between salmon species, there are only rare occurrences of diseases associated with PRV in farmed Atlantic Salmon in BC despite the ubiquitous nature and high prevalence of the virus; and
- Based on laboratory studies conducted with juvenile Sockeye Salmon, PRV from Pacific Canada appears to be infectious but of low virulence under laboratory conditions (Garver et al., 2016a; Garver et al., 2016b; Polinski et al., 2016; Polinski and Garver, 2019), hence PRV is also expected to be of low virulence in adults.

Overall, regardless of the proportion of returning adult Fraser River Sockeye Salmon infected with PRV, the low virulence and absence of significant impact on the likelihood of reaching spawning grounds in PRV-infected Sockeye Salmon suggest a limited impact of PRV on the survival of Fraser River Sockeye Salmon. It was therefore concluded that the potential magnitude of consequences to the abundance of Fraser River Sockeye Salmon would be **negligible**. This conclusion was made with **reasonable uncertainty** given abundant and robust data on the low virulence of PRV in Sockeye Salmon but reliance on surrogate data for determining potential consequences.

Adult Fraser River Sockeye Salmon from nine conservation units have been screened for PRV. Positive detections were reported in four stocks representing four to six of the 24 Fraser River Sockeye Salmon conservation units. However, since no significant spread of infection within the returning adults prior to spawning is expected and given the low virulence of the virus in Sockeye Salmon, it was concluded that the potential magnitude of consequences to the diversity of Fraser River Sockeye Salmon would be **negligible** over two generations (eight years). This conclusion was made with **reasonable uncertainty** given abundant and robust data on the low virulence of PRV in Sockeye Salmon but reliance on surrogate data for determining potential consequences.

5 RISK ESTIMATION

5.1 ABUNDANCE

The risk to the abundance of Fraser River Sockeye Salmon due to infections with PRV attributable to Atlantic Salmon farms in the Discovery Islands area (Table 16) was estimated using the risk matrix combining the results of the likelihood assessment and the results of the consequence assessment to Fraser River Sockeye Salmon abundance (Figure 3).

Table 16. Risk estimation to the abundance of Fraser River Sockeye Salmon resulting from piscine orthoreovirus attributable to Atlantic Salmon farms located in the Discovery Islands area of under current farm practices.

Exposure group	Likelihood assessment	Consequence assessment	Risk to Fraser River Sockeye Salmon abundance
Juvenile Fraser River Sockeye Salmon	Very likely	Negligible	Minimal
Adult Fraser River Sockeye Salmon	Very likely	Negligible	Minimal

Overall, it was concluded that, under the current farm practices, the risk to the abundance of Fraser River Sockeye Salmon as a result of a PRV infection attributable to Atlantic Salmon farms in the Discovery Islands area is **minimal**.

5.2 DIVERSITY

The risk to the diversity of Fraser River Sockeye Salmon due to infections with PRV attributable to Atlantic Salmon farms in the Discovery Islands area (Table 17) was estimated using the risk matrix combining the results of the likelihood assessment and the results of the consequence assessment to Fraser River Sockeye Salmon diversity (Figure 4).

Table 17. Risk estimation to the diversity of Fraser River Sockeye Salmon resulting from piscine orthoreovirus attributable to Atlantic Salmon farms located in the Discovery Islands area of under current farm practices.

Exposure group	Likelihood assessment	Consequence assessment	Risk to Fraser River Sockeye Salmon diversity
Juvenile Fraser River Sockeye Salmon	Very likely	Negligible	Minimal
Adult Fraser River Sockeye Salmon	Very likely	Negligible	Minimal

Overall, it was concluded that, under the current farm practices, the risk to the diversity of Fraser River Sockeye Salmon as a result of a PRV infection attributable to Atlantic Salmon farms in the Discovery Islands area is **minimal**.

6 SOURCES OF UNCERTAINTIES

Total uncertainty includes both variability, which is a function of the system that is not reducible with additional measurements, and lack of knowledge that may be reduced with additional data or expert opinion (Vose, 2008). There are uncertainties associated with both the likelihood and consequence assessments.

6.1 LIKELIHOOD ASSESSMENT

The main uncertainties related to the likelihood assessment are:

- the source(s) and survival of PRV in the marine environment are unknown;
- the variability and knowledge gaps about precise migration routes of lake-type Fraser River Sockeye Salmon through the Discovery Islands area;
- the shedding rates from PRV infected Atlantic Salmon are unknown; and
- the minimal infectious doses of PRV in Sockeye Salmon are unknown.

6.2 CONSEQUENCE ASSESSMENT

The main uncertainties in the consequence assessments for both abundance and diversity resulted from:

- the persistence of PRV infection in Sockeye Salmon is unknown;
- the lack of understanding of how PRV spreads within migrating fish populations; and
- minimal information on PRV prevalence and impact on different conservation units of Fraser River Sockeye Salmon.

7 CONCLUSIONS

The assessment concluded that PRV attributable to Atlantic Salmon farms in the Discovery Islands area poses minimal risk to Fraser River Sockeye Salmon abundance and diversity under the current farm practices.

The attribution of the minimal risk was mainly influenced by the potential magnitude of consequences to Fraser River Sockeye Salmon. Despite concluding that it is very likely that at least one Fraser River Sockeye Salmon would become infected with PRV attributable to Atlantic

Salmon farms in the Discovery Islands area, the consequence of such infections to both Fraser River Sockeye Salmon abundance and diversity would be expected to be negligible.

There are important sources of uncertainties associated to the determination of the risk to Fraser River Sockeye Salmon due to PRV attributable to Atlantic Salmon farms in the Discovery Islands area. The main uncertainties are related to shedding rate in PRV-infected Atlantic Salmon, PRV survival in the marine environment, and the minimum infectious doses of PRV required to infect Sockeye Salmon. Additionally, there is a lack of knowledge about the persistence of PRV infections in Sockeye Salmon, the spread of infections in migrating Fraser River Sockeye Salmon and impact on different conservation units of Fraser River Sockeye Salmon. Conclusions of this risk assessment should be reviewed as new research findings fill knowledge gaps.

8 REFERENCES CITED

Adamek, M., Hellmann, J., Flamm, A., Teitge, F., Vendramin, N., Fey, D., Riße, K., Blakey, F., Rimstad, E. and Steinhagen, D. 2018. Detection of piscine orthoreoviruses (PRV-1 and PRV-3) in Atlantic salmon and rainbow trout farmed in Germany. Transbound Emerg. Dis. 66: 14-21.

Chandler, P. C., Foreman, M. G. G., Ouellet, M., Mimeault, C. and Wade, J. 2017. Oceanographic and environmental conditions in the Discovery Islands, British Columbia. DFO Can. Sci. Adv. Sec. Res. Doc. 2017/071. viii + 51 p.

Cohen, B. I. 2012a. Recommendations, summary, process. *In* The uncertain future of Fraser River Sockeye. Minister of Public Works and Government Services Canada. Publishing and Depository Services, Ottawa, ON. Vol 3: 211 p.

Cohen, B. I. 2012b. The sockeye fishery. The Uncertain Future of Fraser River Sockeye. Vol. 1. Minister of Public Works and Government Services Canada, Publishing and Depository Services, Ottawa, ON. 687 p.

Cox, L. A. T. J. 2008. What's wrong with risk matrices? Risk. Anal. 28(2): 497-512.

Cudmore, B., Mandrak, N. E., Dettmers, J., Chapman, D. C. and Kolar, C. S. 2012. Binational ecological risk assessment of bigheaded carps (*Hypophthalmichthys* spp.) for the Great Lakes basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/114. 57 p.

DFO. 2015. Marine finfish aquaculture licence under the Fisheries Act. Aquaculture Management Division.

DFO. 2018a. The 2017 Fraser Sockeye Salmon (*Oncorhynchus nerka*) integrated biological status re-assessment under the wild salmon policy. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2018/017. 17 p.

DFO. 2018b. Licences for introductions and transfers. Licensing requirements specific to BC. Aquaculture Management Division.

DFO. 2018c. Results of DFO fish health audits of British Columbian marine finfish aquaculture sites, by facility. Fisheries and Oceans Canada.

Di Cicco, E., Ferguson, H. W., Kaukinen, K., Schulze, A. D., Li, S., Tabata, A., Gunther, O. P., Mordecai, G., Suttle, C. A. and Miller, K. M. 2018. The same strain of Piscine orthoreovirus (PRV-1) is involved with the development of different, but related, diseases in Atlantic and Pacific salmon in British Columbia. FACETS 3: 599-641.

Di Cicco, E., Ferguson, H. W., Schulze, A. D., Kaukinen, K. H., Li, S., Vanderstichel, R., Wessel, O., Rimstad, E., Gardner, I. A., Hammell, K. L. and Miller, K. M. 2017. Heart and skeletal muscle inflammation (HSMI) disease diagnosed on a British Columbia salmon farm through a longitudinal farm study. PLoS One 12(2): 1-31.

FAO. 2008. Understanding and applying risk analysis in aquaculture. *In* FAO Fisheries and Aquaculture Technical Paper 519. Rome, Italy. 304 p.

Finstad, Ø. W., Dahle, M. K., Lindholm, T. H., Nyman, I. B., Løvoll, M., Wallace, C., Olsen, C. M., Storset, A. K. and Rimstad, E. 2014. Piscine orthoreovirus (PRV) infects Atlantic salmon erythrocytes. Vet. Res. 45(35): 1-13.

Foreman, M., Guo, M., Garver, K. A., Stucchi, D., Chandler, P., Wan, D., Morrison, J. and Tuele, D. 2015a. Modelling infectious hematopoietic necrosis virus dispersion from marine salmon farms in the Discovery Islands, British Columbia, Canada. PLoS One 10(6): e0130951.

Foreman, M. G. G., Chandler, P. C., Stucchi, D. J., Garver, K. A., Guo, M., Morrison, J. and Tuele, D. 2015b. The ability of hydrodynamic models to inform decisions on the siting and management of aquaculture facilities in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/005. vii + 49 p.

Foreman, M. G. G., Stucchi, D. J., Garver, K. A., Tuele, D., Isaac, J., Grime, T., Guo, M. and Morrison, J. 2012. A circulation model for the Discovery Islands, British Columbia. Atmos. Ocean 50(3): 301-316.

Furey, N. B. 2016. Migration ecology of juvenile Pacific salmon smolts : the role of fish condition and behaviour across landscapes. Thesis (Doctor of Philosophy) Forestry, University of British Columbia. Vancouver. 201 p.

Gale, P., Brouwer, A., Ramnial, V., Kelly, L., Kosmider, R., Fooks, A. R. and Snary, E. L. 2010. Assessing the impact of climate change on vector-borne viruses in the EU through the elicitation of expert opinion. Epidemiol. Infect. 138(2): 214-225.

Garver, K. A., Johnson, S. C., Polinski, M. P., Bradshaw, J. C., Marty, G. D., Snyman, H. N., Morrison, D. B. and Richard, J. 2016a. Piscine orthoreovirus from western North America is transmissible to Atlantic Salmon and Sockeye Salmon but fails to cause heart and skeletal muscle inflammation. PLoS One. 11(1): e0146229.

Garver, K. A., Marty, G. D., Cockburn, S. N., Richard, J., Hawley, L. M., Müller, A., Thompson, R. L., Purcell, M. K. and Saksida, S. 2016b. Piscine reovirus, but not jaundice syndrome, was transmissible to Chinook Salmon, *Oncorhynchus tshawytscha* (Walbaum), Sockeye Salmon, *Oncorhynchus nerka* (Walbaum), and Atlantic Salmon, *Salmo salar* L. J. Fish Dis. 39(2): 117-128.

GESAMP. 2008. Assessment and communication of environmental risks in coastal aquaculture. *In* Reports and Studies GESAMP. Rome, Italy. FAO 76: 198 p.

Grant, A. A. M. and Jones, S. R. M. 2010. Pathways of effects between wild and farmed finfish and shellfish in Canada: potential factors and interactions impacting the bi-directional transmission of pathogens. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/018. vi + 58 p.

Grant, S. C. H., Holt, C., Wade, J., Mimeault, C., Burgetz, I. J., Johnson, S. and Trudel, M. 2018. Summary of Fraser River Sockeye Salmon (*Oncorhynchus nerka*) ecology to inform pathogen transfer risk assessments in the Discovery Islands, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/074. v + 30 p.

Gunnarsdóttir, H. M., Sigurðardóttir, H., Bragason, B. Þ. and Guðmundsdótti, S. 2018. A survey of three viruses in wild and cultured salmon in Iceland. *In* 8th International Symposium on Aquatic Animal Health. Charlottetown. American Fisheries Society Fish Health Section. pp 405.

Haatveit, H. M., Wessel, O., Markussen, T., Lund, M., Thiede, B., Nyman, I. B., Braaen, S., Dahle, M. K. and Rimstad, E. 2017. Viral protein kinetics of piscine orthoreovirus infection in Atlantic salmon blood cells. Viruses. 9(3): 49.

Hauge, H., Dahle, M., Moldal, T., Thoen, E., Gjevre, A. G., Weli, S., Alarcon, M. and Grove, S. 2016. Piscine orthoreovirus can infect and shed through the intestine in experimentally challenged Atlantic salmon (*Salmo salar* L.). Vet. Res. 47(1): 57.

Hrushowy, S. 2018. A molecular investigation of the dynamics of piscine orthoreovirus in a wild sockeye salmon community on the central coast of British Columbia. Thesis (Master of Science) Biological Sciences, Simon Fraser University. Vancouver. 137 p.

ISO. 2009. Risk management - Risk assessment techniques. *In* International Standard. International Standard. IEC/FDIS 31010. 90 p.

Jeffries, K. M., Hinch, S. G., Gale, M. K., Clark, T. D., Lotto, A. G., Casselman, M. T., Li, S. R., Rechisky, E. L., Porter, A. D., Welch, D. W. and Miller, K. M. 2014. Immune response genes and pathogen presence predict migration survival in wild salmon smolts. Mol. Ecol. 23(23): 5803-5815.

Johansen, L. H., Jensen, I., Mikkelsen, H., Bjørn, P. A., Jansen, P. A. and Bergh, Ø. 2011. Disease interaction and pathogens exchange between wild and farmed fish populations with special reference to Norway. Aquaculture 315: 167-186.

Jones, S. R. M., Bruno, D. W., Madsen, L. and Peeler, E. J. 2015. Disease management mitigates risk of pathogen transmission from maricultured salmonids. Aquac. Environ. Interact. 6: 119-134.

Kibenge, M. J., Iwamoto, T., Wang, Y., Morton, A., Godoy, M. G. and Kibenge, F. S. 2013. Whole-genome analysis of piscine reovirus (PRV) shows PRV represents a new genus in family Reoviridae and its genome segment S1 sequences group it into two separate sub-genotypes. Virology 10(230): 1-20.

Kongtorp, R., Taksdal, T. and Lyngøy, A. 2004a. Pathology of heart and skeletal muscle inflammation (HSMI) in farmed Atlantic salmon *Salmo salar*. Dis. Aquat. Org. 59(3): 217-224.

Kongtorp, R. T., Halse, M., Taksdal, T. and Falk, K. 2006. Longitudinal study of a natural outbreak of heart and skeletal muscle inflammation in Atlantic salmon, *Salmo salar* L. J. Fish Dis. 29(4): 233-244.

Kongtorp, R. T., Kjerstad, A., Taksdal, T., Guttvik, A. and Falk, K. 2004b. Heart and skeletal muscle inflammation in Atlantic salmon, *Salmo salar* L.: a new infectious disease. J. Fish Dis. 27(6): 351-358.

Laurin, E., Jaramillo, D., Vanderstichel, R., Ferguson, H., Kaukinen, K., Schulze, A. D., Keith, I., Gardner, I. and Miller, K. M. 2019. Histopathological and novel high-throughput molecular monitoring data from farmed salmon (*Salmo salar* and *Oncorhynchus* spp.) in British Columbia, Canada, from 2011-2013. Aquaculture 499: 220-234.

Lund, M., Krudtaa Dahle, M., Timmerhaus, G., Alarcon, M., Powell, M., Aspehaug, V., Rimstad, E. and Jorgensen, S. M. 2017. Hypoxia tolerance and responses to hypoxic stress during heart and skeletal muscle inflammation in Atlantic salmon (*Salmo salar*). PLoS One 12(7): e0181109.

Mandrak, N. E., Cudmore, B. and Chapman, P. M. 2012. National detailed-level risk assessment guidelines: assessing the biological risk of aquatic invasive species in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/092. vi + 17 p.

Markussen, T., Tengs, T., Dhamotharan, K., Nyman, I. B., Wessel, Ø., Dahle, M. K. and Rimstad, E. 2018. Analyses of genome sequences and protein structure of strains of piscine orthoreovirus (PRV1) with putative different virulence in Atlantic salmon (*Salmo salar*). 8th International Symposium on Aquatic Animal Health. Charlottetown, PEI. September 2-6. 405 p.

Marty, G. D., Morrison, D. B., Bidulka, J., Joseph, T. and Siah, A. 2015. Piscine reovirus in wild and farmed salmonids in British Columbia, Canada: 1974–2013. J. Fish Dis. 38(8): 713-728.

Miller, K. M., Teffer, A., Tucker, S., Li, S. R., Schulze, A. D., Trudel, M., Juanes, F., Tabata, A., Kaukinen, K. H., Ginther, N. G., Ming, T. J., Cooke, S. J., Hipfner, J. M., Patterson, D. A. and Hinch, S. G. 2014. Infectious disease, shifting climates, and opportunistic predators: cumulative factors potentially impacting wild salmon declines. Evol. Appl. 7(7): 812-855.

Mimeault, C., Aubry, P., Wan, D., Wade, J., Boily, F., Jones, S. R. M., Johnson, S., Foreman, M. G. G., Chandler, P., Garver, K. A., Holt, C., Burgetz, I. J. and Parsons, G. J. 2019a. Assessment of the risk to Fraser River Sockeye Salmon due to *Aeromonas salmonicida* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/017. In press.

Mimeault, C., Jones, S. R. M., Wade, J., Aubry, P., Johnson, S., Foreman, M. G. G., Garver, K. A., Holt, C., Boily, F., Burgetz, I. J. and Parsons, G. J. 2019b. Assessment of the risk to Fraser River Sockeye Salmon due to *Piscirickettsia salmonis* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/021. In press.

Mimeault, C., Wade, J., Boily, F., Johnson, S., Jones, S. R. M., Aubry, P., Foreman, M. G. G., Garver, K. A., Holt, C., Burgetz, I. J. and Parsons, G. J. 2019c. Assessment of the risk to Fraser River Sockeye Salmon due to *Yersinia ruckeri* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/023. In press.

Mimeault, C., Wade, J., Boily, F., Johnson, S., Jones, S. R. M., Aubry, P., Malcolm, G., Foreman, M. G. G., Chandler, P. C., Wan, D., Garver, K. A., Holt, C., Burgetz, I. J. and Parsons, G. J. 2019d. Assessment of the risk to Fraser River Sockeye Salmon due to *Renibacterium salmoninarum* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/019. In press.

Mimeault, C., Wade, J., Foreman, M. G. G., Chandler, P. C., Aubry, P., Garver, K. A., Grant, S. C. H., Holt, C., Jones, S., Johnson, S., Trudel, M., Burgetz, I. J. and Parsons, G. J. 2017. Assessment of the risk to Fraser River Sockeye Salmon due to infectious hematopoietic necrosis virus (IHNV) transfer from Atlantic Salmon farms in the Discovery Islands, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/075. vii + 75 p.

Morton, A., Routledge, R., Hrushowy, S., Kibenge, M. and Kibenge, F. 2017. The effect of exposure to farmed salmon on piscine orthoreovirus infection and fitness in wild Pacific salmon in British Columbia, Canada. PLoS One 0188793: 1-18.

Nekouei, O., Vanderstichel, R., Ming, T., Kaukinen, K. H., Thakur, K., Tabata, A., Laurin, E., Tucker, S., Beacham, T. D. and Miller, K. M. 2018. Detection and assessment of the distribution of infectious agents in juvenile Fraser River Sockeye Salmon, Canada, in 2012 and 2013. Front. Microbiol. 9: 3221.

OIE. 2010. Handbook on import risk analysis for animal and animal products. Introduction to qualitative risk analysis. Introduction and qualitative risk analysis. 2nd ed. Vol. 1. The World Organisation for Animal Health, Paris, France. 100 p.

Palacios, G., Løvoll, M., Tengs, T., Hornig, M., Hutchison, S., Hui, J., Kongtorp, R.-T., Savji, N., Bussetti, A. V., Solovyov, A., Kristoffersen, A. B., Celone, C., Street, C., Trifonov, V., Hirschberg, D. L., Rabadan, R., Egholm, M., Rimstad, E. and Lipkin, W. I. 2010. Heart and skeletal muscle inflammation of farmed salmon is assoiciated with infection with a novel reovirus. PLoS One 5(7): e11487.

Peeler, E. J. and Thrush, M. A. 2009. Assessment of exotic fish disease introduction and establishment in the United Kingdom via live fish transporters. Dis. Aquat. Org. 83: 85-95.

Polinski, M. P., Bradshaw, J. C., Inkpen, S. M., Richard, J., Fritsvold, C., Poppe, T. T., Rise, M. L., Garver, K. A. and Johnson, S. C. 2016. *De novo* assembly of Sockeye salmon kidney transcriptomes reveal a limited early response to piscine reovirus with or without infectious hematopoietic necrosis virus superinfection. BMC Genom. 17(1): 848.

Polinski, M. P. and Garver, K. A. 2019. Characterization of piscine orthoreovirus (PRV) and associated diseases to inform pathogen transfer risk assessments in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/035. iii + 35. p.

Polinski, M. P., Marty, G. D., Snyman, H. N. and Garver, K. A. 2019. Piscine orthoreovirus demonstrates high infectivity but low virulence in Atlantic salmon of Pacific Canada. Sci. Rep. 40025: doi: 10.1038/s41598-41019-40025-41597.

Purcell, M., Powers, R., Evered, J., Kerwin, J., Meyers, T. R., Stewart, B. and Winton, J. 2018. Molecular testing of adult Pacific salmon and trout (*Oncorhynchus* spp.) for several RNA viruses demonstrates widespread distribution of piscine orthoreovirus in Alaska and Washington. J. Fish Dis. 41(2): 347-355.

Rechisky, E. L., Stevenson, C., Porter, A. D., Welch, D. W., Furey, N. B., Healy, S., Johnston, S. and Hinch, S. G. 2018. Telemetry-based estimates of early marine survival and residence time of juvenile sockeye salmon in the Strait of Georgia and Queen Charlotte Strait, 2017. *In* State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2017. Can. Tech. Rep. Fish. Aquat. Sci. 3266. viii + 245 p.

Stevenson, C. F. 2018. The influence of smolt age and physiological condition on survival and behaviour of wild migrating juvenile sockeye salmon (*Oncorhynchus nerka*) in British Columbia. Thesis (Masters of Science) Forestry, Simon Fraser University. Vancouver, BC. 121 p.

Stoddard, E. M. 1993. Fraser River sockeye health study 1993 field collection, and bacteriological, virological and histological analysis of data collected: final report. EMS Aquatic Services, Vancouver, B.C. 23 p.

Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., Kvamme, B. O., Boxaspen, K. K., Bjorn, P. A., Finstad, B., Madhun, A. S., Morton, H. C. and Svasand, T. 2014. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES J. Mar. Sci. 72(3): 997-1021.

Teffer, A. K., Hinch, S. G., Miller, K. M., Patterson, D. A., Farrell, A. P., Cooke, S. J., Bass, A. L., Szekeres, P. and Juanes, F. 2017. Capture severity, infectious disease processes and sex influence post-release mortality of sockeye salmon bycatch. Conserv. Physiol. 5(1): 1-33.

Thakur, K. K., Vanderstichel, R., Kaukinen, K., Nekouei, O., Laurin, E. and Miller, K. M. 2019. Infectious agent detections in archived Sockeye salmon (*Onchohynchus nerka*) samples from British Columbia, Canada (1985-94). J. Fish Dis. 42(4): 533-547.

Vose, D. 2008. Risk analysis: a quantitative guide. 3rd ed. Wiley, Chichester, England. 735 p.

Wade, J. 2017. British Columbia farmed Atlantic Salmon health management practices. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/072. vi + 55 p.

Warheit, K. 2018. WDFW denies perit for company to place 800,000 Atlantic salmon into Puget Sound net pens. Washington Department of Fish and Wildlife. Olympia WA.

Wessel, Ø., Braaen, S., Alarcon, M., Haatveit, H., Roos, N., Markussen, T., Tengs, T., Dahle, M. K. and Rimstad, E. 2017. Infection with purified piscine orthoreovirus demonstrates a causal relationship with heart and skeletal muscle inflammation in Atlantic salmon. PLoS One 12(8): e0183781.

Wessel, Ø., Olsen, C. M., Rimstad, E. and Dahle, M. K. 2015. Piscine orthoreovirus (PRV) replicates in Atlantic salmon (*Salmo salar* L.) erythrocytes ex vivo. Vet. Res. 46(1): 1-11.

Zhang, Y., Polinski, M., Morrison, P. R., Brauner, C. J., Farrell, A. P. and Garver, K. A. 2019. High-load reovirus infections do not imply physiological impairment in salmon. Front. Physiol. 10:114: 1-12.

9 APPENDICES

9.1 APPENDIX A: ATLANTIC SALMON PRODUCTION CYCLES IN THE DISCOVERY ISLANDS AREA

Atlantic Salmon production cycles in the Discovery Islands area were summarized in November 2018 based on dates of fish transfers between January 2013 and November 2018.

Grow-out periods in the Discovery Islands area ranged between 12 and 23 months (average=17 months, n=27 cycles) from the beginning of fish transfer to grow-out sites to the end of harvesting periods. Fish can be stocked between 2 and 14 months (average=7 months, n=23 cycles) on nursery sites prior to being transferred to grow-out sites in the Discovery Islands area.

Between January 2013 and November 2018, fish transfers to grow-out sites in the Discovery Islands area occurred in every month of the year with most of them occurred in May and June (Figure 6). Within a given production cycle, fish are usually transferred within a given month but can sometime extend over four months.

Figure 6. Production cycles initiated between January 2013 and December 2017 on Atlantic Salmon farms in the Discovery Islands area. Only marine grow-out sites stocked with fish transferred from seawater nursery sites are included. Production cycles on any given farm are represented on a single row when possible or multiple rows when nursery and grow-out periods overlap (farms D and H). Grey bars represent periods with fish stocked at marine nursery sites while black bars represent periods of marine grow-out sites in the Discovery Islands area. Data summarized in November 2018 including predicted harvest dates out to mid-2019. Data source for production cycles: DFO Aquaculture Management.

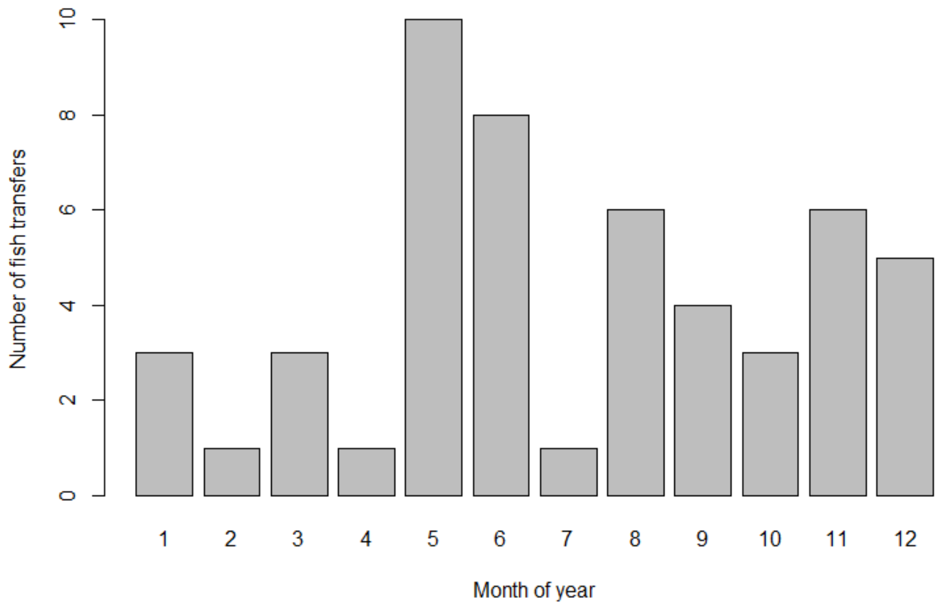

Figure 7. Atlantic Salmon transfers to marine grow-out sites in the Discovery Islands area between January 2013 and June 2018. Data include first transfers over a total of 28 production cycles from hatcheries and seawater nursery sites to marine grow-out sites. Data provided by DFO Aquaculture Management.

9.2 APPENDIX B: DFO AUDIT DEFICIENCIES

Table 18. Number of deficiencies identified during audits conducted by Fisheries and Oceans Canada on Atlantic Salmon farms 2011-2017 in British Columbia. Data provided by DFO Aquaculture Management (updated from Wade, 2017).

DFO audit deficiency categories	2011	2012	2013	2014	2015	2016	2017	Total
Carcass retrieval protocol or record keeping needs improvement	2	8	4	23	23	21	18	99
Current finfish licence was not posted at facility	0	0	2	0	1	1	3	7
Disease contingency or mass mortality information or records needs improvement	2	1	0	0	0	9	11	23
Fish euthanasia and/or methods not recorded	3	1	0	0	0	0	1	5
Footbaths or sanitizers needs improvement	0	1	3	11	3	4	1	23
Husbandry or record keeping as per COL Appendix VIII-A or VIII-B needs improvement	2	5	4	3	6	2	3	25
Lice protocol or lice records as per COL VII or VII-A needs improvement	21	17	15	18	19	9	26	125
Mooring signage needs improvement	21	6	7	6	9	6	3	58
Mortality assessment or classification needs improvement	0	0	0	0	0	0	0	0
Nutritional or medicated feed protocol concerns	0	0	2	1	3	0	1	7
Training documentation is not up-to-date	0	4	0	3	5	0	1	13
Transfer records are not complete or up-to-date	25	9	9	3	3	3	6	58
Visitor protocol communication needs improvement	7	2	4	2	0	0	1	16
Water quality monitoring, equipment or record keeping needs improvement	0	0	1	0	0	0	1	2
Wild fish mortality records need clarification	0	1	1	0	0	2	3	7
Total # deficiencies	83	55	52	70	72	57	79	468
# audits	58	102	96	99	110	106	111	682
# farms with deficiencies	40	35	31	41	45	41	29	262
Average # deficiencies/audit	1.43	0.54	0.54	0.71	0.65	0.54	0.71	0.73