Fisheries and Oceans Canada | Pêches et Océans Canada
Ecosystems and Oceans Science | Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2019/017

National Capital Region

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

C. Mimeault[1], P. Aubry[2], D. Wan[3], J. Wade[4], F. Boily[1], S.R.M. Jones[5], S. Johnson[5], M.G.G. Foreman[3], P.C. Chandler[3], K.A. Garver[5], C. Holt[5], I.J. Burgetz[1], and G.J. Parsons[1]

[1]Fisheries and Oceans Canada
Aquaculture, Biotechnology and Aquatic Animal Health Science
200 Kent, Ottawa, ON K1A 0E6

[2]Canadian Food Inspection Agency
Animal Health Science Division
1400 Merivale, Ottawa, ON K1A 0Y9

[3]Fisheries and Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Road, Sidney, BC V8L 5T5

[4]Fundy Aqua Services Inc.
1859 Delanice Way, Nanoose Bay, BC V9P 9B3

[5]Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road, Nanaimo, BC V9T 6N7

November 2020

Canada

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.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

© Her Majesty the Queen in Right of Canada, 2020
ISSN 1919-5044

Correct citation for this publication:

Mimeault, C., Aubry, P., Wan, D., Wade, J., Boily, F., Jones, S.R.M., Johnson, S., Foreman, M.G.G., Chandler, P.C., Garver, K.A., Holt, C., Burgetz, I.J. and Parsons, G.J. 2020. 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. ix + 64 p.

Aussi disponible en français :

Mimeault, C., Aubry, P., Wan, D., Wade, J., Boily, F., Jones, S.R.M., Johnson, S., Foreman, M.G.G., Chandler, P.C., Garver, K.A., Holt, C., Burgetz, I.J. et Parsons, G.J. 2020. Évaluation du risque pour le saumon rouge du fleuve Fraser attribuable au transfert de la bactérie Aeromonas salmonicida *à partir des fermes d'élevage de saumon atlantique situées dans la région des îles Discovery (Colombie-Britannique). Secr. can. de consult. sci. du MPO. Doc. de rech. 2019/017.*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

Acute: characterized by a short and relatively severe course

Carrier: an infected animal that sheds pathogenic organisms but shows no sign of disease

Chronic: a disease condition that is persistent or long lasting

Clinical: outward appearance of a disease in a living organism

Colony-forming unit (CFU): is a unit used to estimate the number of viable bacterial cells in a sample, where viability is assessed as the ability to multiply on an artificial growth medium (e.g., agar plate)

Disease: condition in which the normal function or structure of part of the body or a bodily function is impaired

Epidemiological unit: a group of animals that share approximately the same risk of exposure to a pathogenic agent within 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)

Incubation period: period of time between infection and onset of clinical signs

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

Infectious period: the period of time during which individuals are infectious (i.e., shedding viable organisms)

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: unexpected occurrence of mortality or disease in a population

Prevalence: the 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 in a given population at one specific time

Silver: fresh mortalities

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: refers to a 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 (*Oncorhynchus nerka*) due to pathogens on marine Atlantic Salmon (*Salmo salar*) farms located in the Discovery Islands area in British Columbia (BC).

This document is the assessment of the risk to Fraser River Sockeye Salmon due to *Aeromonas salmonicida* on Atlantic Salmon farms in the Discovery Islands area of BC under current farm practices. The risk assessment was conducted in three main steps: first, a likelihood assessment which includes four consecutive assessment steps (farm infection, pathogen release, exposure of susceptible wild fish, and infection of susceptible wild fish); second, a consequence assessment; and third, a risk estimation which combines the first two steps.

Aeromonas salmonicida is the causative agent of furunculosis, and is endemic to BC where it has been detected both in wild and farmed salmon. Based on evidence of infection and disease on Atlantic Salmon farms between 2002 and 2017, it is unlikely, with reasonable certainty, that farmed Atlantic Salmon in the Discovery Islands area will become infected with *A. salmonicida* in any given year under the current farm practices. However, when infected, the bacterium is extremely likely, with high certainty, to be released from farmed Atlantic Salmon into the marine environment given evidence that infected Atlantic Salmon in seawater can shed the bacterium. Considering the migration window of Fraser River Sockeye Salmon through the Discovery Islands area and the timing of *A. salmonicida* infections on farms, it is likely that at least one juvenile and adult, both with reasonable certainty, would be exposed to the bacterium released from infected farms in any given year. Under such exposure, it is very unlikely that Fraser River Sockeye Salmon would get infected with *A. salmonicida* attributable to Atlantic Salmon farms located in the Discovery Islands area given the infection pressure. Overall, it was concluded that the likelihood that Fraser River Sockeye Salmon would become infected with *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area is very unlikely under the current fish health management practices.

In the event of a very unlikely infection of Fraser River Sockeye Salmon with *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area, the potential magnitude of consequences to Fraser River Sockeye Salmon abundance and diversity resulting from an infection was determined to be negligible given that an infection acquired at the juvenile stage would not be expected to spread within the population at sea, and that an infection acquired at the adult stage would not have time to spread before reaching spawning grounds. These conclusions were reached with reasonable to high uncertainty given significant knowledge gaps.

Overall, the assessment concluded that *A. salmonicida* 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. This risk assessment 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 and is a priority of the Minister of Fisheries, Oceans and the Canadian Coast Guard.

It is recognized that there are interactions between aquaculture operations and the environment (Grant and Jones, 2010; Foreman et al., 2015). 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 located in the Discovery Islands area 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.

This document assesses the risk to Fraser River Sockeye Salmon (*Oncorhynchus nerka*) attributable to *Aeromonas salmonicida*, the causative agent of furunculosis, from Atlantic Salmon farms in the Discovery Islands area in BC. This pathogen was selected to undergo a formal pathogen transfer risk assessment given that furunculosis had been reported at the farm level on Atlantic Salmon farms in the Discovery Islands area.

Although there are reports of some atypical strains of *A. salmonicida* causing disease in salmonids in many countries (Evelyn, 1971; Wiklund and Dalsgaard, 1998; Hiney and Olivier, 1999), furunculosis in wild and pen-reared salmon on the Pacific coast of Canada and the United States of America (USA) has mainly been associated with the typical strain, *A. salmonicida* subsp. *salmonicida* (Kent, 1992; MacDiarmid, 1994). Both typical and atypical strains are considered in this risk assessment.

Risks posed to other wild fish populations and related to other fish farms, pathogens, and regions of BC are not included in the scope of the current risk assessment.

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 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 the bacterium *A. salmonicida* (typical and atypical strains) attributable to Atlantic Salmon farms in the Discovery Islands area.

2.2.2 Hazard characterisation

Boily et al. (2019) summarized the relevant characteristics of *A. salmonicida* and furunculosis (e.g., pathogen distribution, virulence, survival in the environment, susceptible species, shedding rates in Atlantic Salmon, infectious doses in Pacific salmon) and identified knowledge gaps relevant to this risk assessment. The review also includes a summary of the occurrence of *A. salmonicida* and furunculosis on Atlantic Salmon farms in BC. Additional details specific to Atlantic Salmon farms located in the Discovery Islands area are included in this document.

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 active Atlantic Salmon farms operating in the Discovery Islands area (Fish Health Surveillance Zone 3-2) and in close proximity (three farms in Fish Health Surveillance Zone 3-3 to the northwest of Fish Health Surveillance Zone 3-2) (refer to Figure 1 and Table 1) and includes the same 18 farms as in 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.

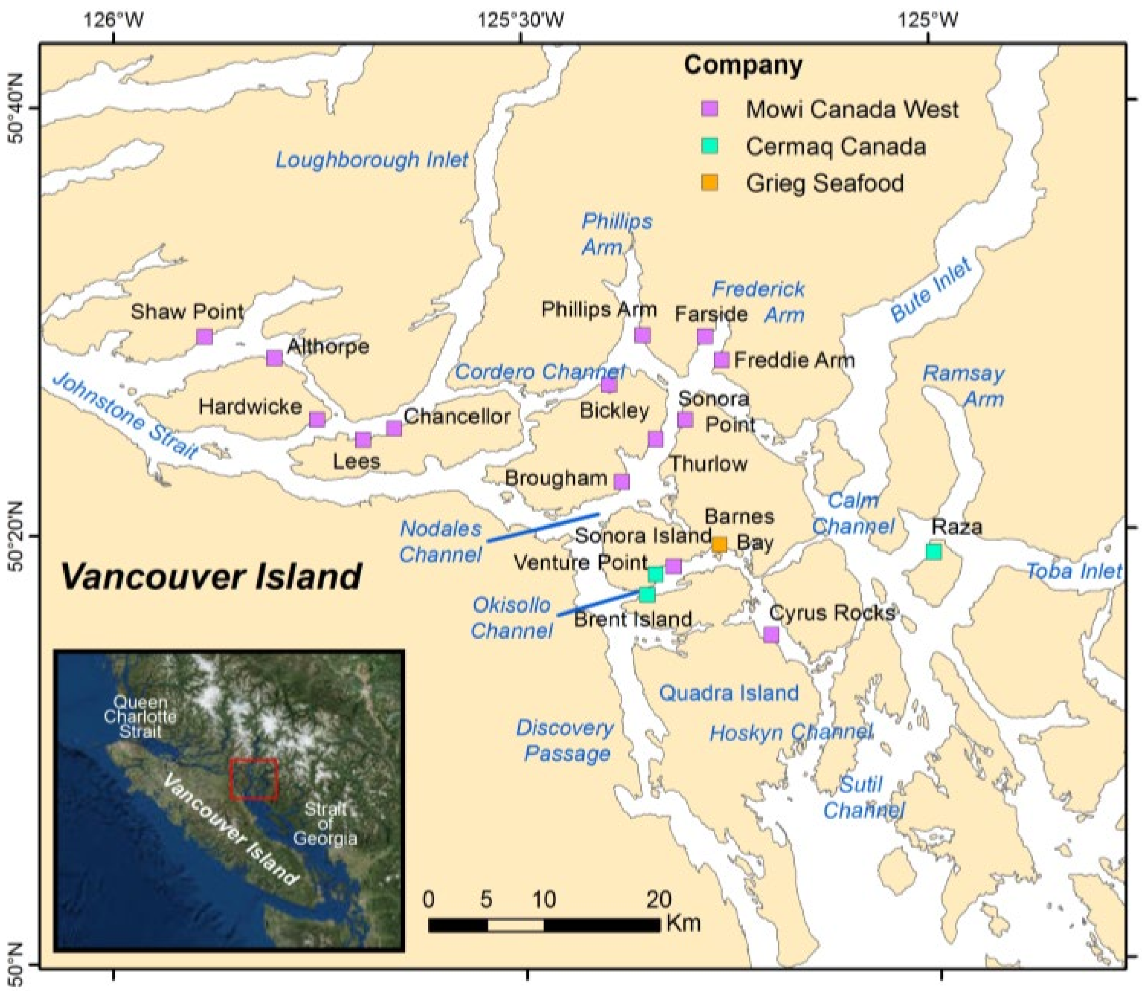

Figure 1. Locations of Atlantic Salmon farms in the Discovery Islands area (Fish Health Surveillance Zone 3-2 and three farms in Fish Health Surveillance Zone 3-3) included in this risk assessment. Symbol size for fish farms is not to scale. The insert illustrates the location of the Discovery Islands area in British Columbia. Adapted from Mimeault et al. (2017).

Table 1. List of the 18 active 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 (formerly 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

2.2.4 Risk question

What is the risk to Fraser River Sockeye Salmon abundance and diversity due to the transfer of *A. salmonicida* 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 Organization 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 assessment is done 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 *A. salmonicida* infection attributable to Atlantic Salmon farms in the Discovery Islands area on the abundance and diversity of Fraser River Sockeye Salmon.

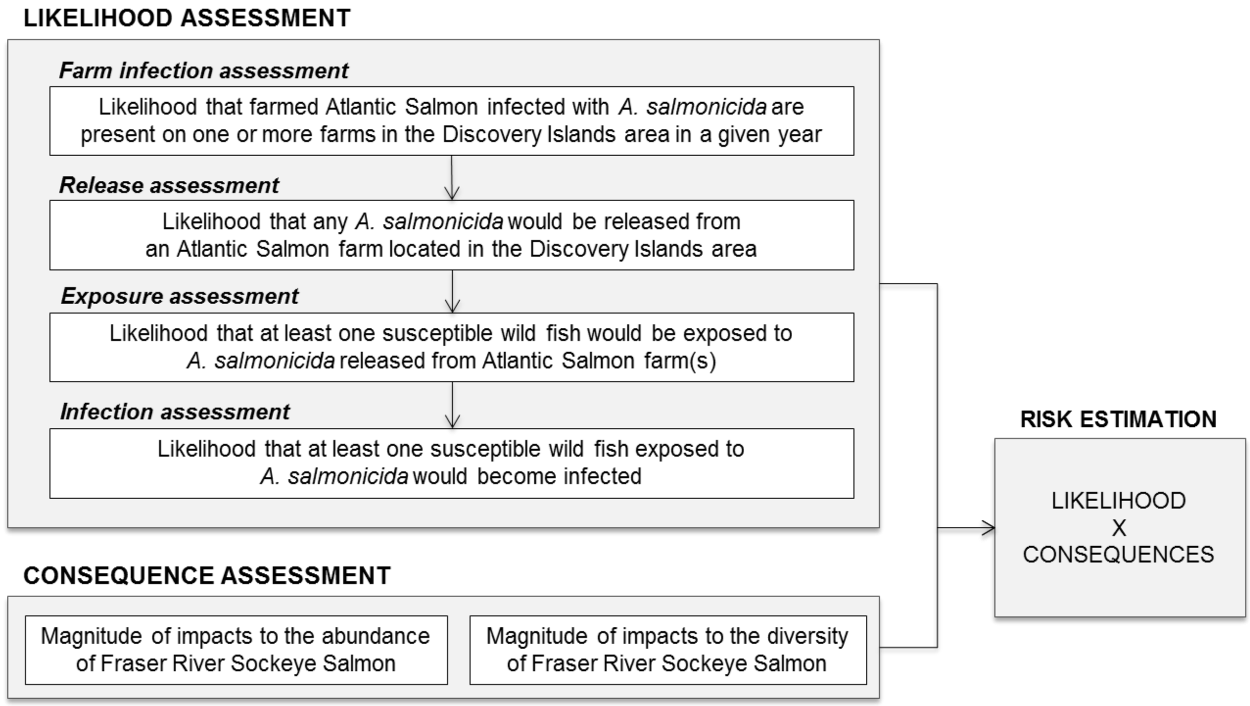

Figure 2. Conceptual model to assess the risks to Fraser River Sockeye Salmon resulting from Aeromonas salmonicida *attributable to Atlantic Salmon farms located in the Discovery Islands area, British Columbia. Adapted from Mimeault et al. (2017).*

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.

Categories	Definitions
Extremely likely	Event is expected to occur, will happen
Very likely	Event is very likely to occur
Likely	Event is likely to occur
Unlikely	Event is unlikely to occur, not likely but could occur
Very unlikely	Event is very unlikely to occur
Extremely unlikely	Event has little to no chance to occur, insignificant, negligible

Table 3. Categories and definitions used to describe the potential consequences to the abundance of Fraser River Sockeye Salmon.

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.

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 CUs 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.

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.

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). However, when events are independent but not mutually exclusive, i.e., could occur concurrently, the adoption of the highest individual likelihood might underestimate the overall likelihood. Uncertainty is reported individually for each ranking without combination.

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 DFO's 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 the relevant scale of consequences for fisheries management and policy purposes, existing policy and current management risk tolerance relevant to the risk assessments.

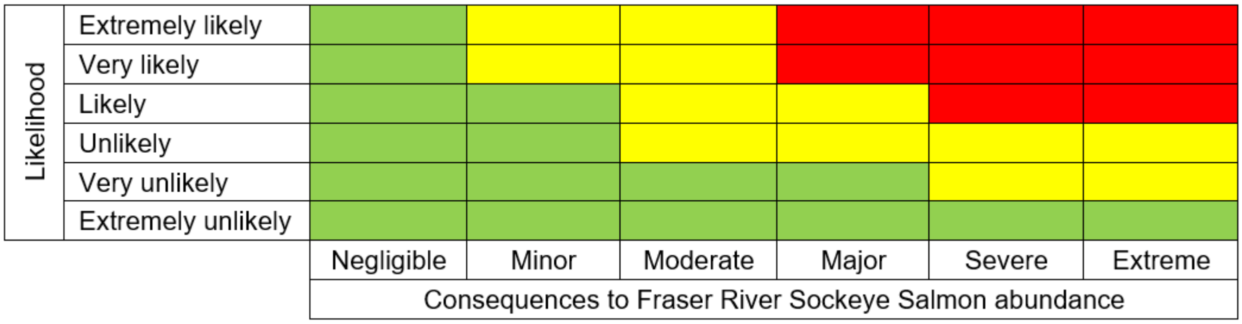

Figure 3. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon abundance. Green, yellow and red represent minimal, moderate and high risk, respectively.

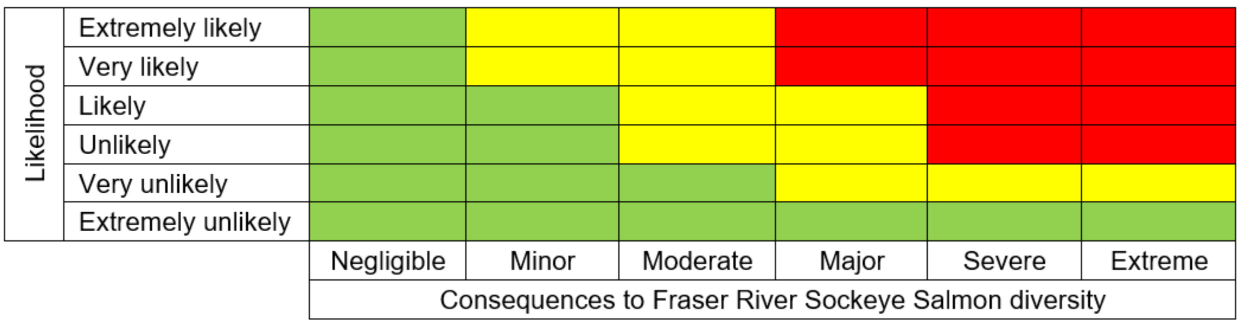

Figure 4. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon diversity. Green, yellow and red represent minimal, moderate and high risk, respectively.

3 LIKELIHOOD ASSESSMENT

The likelihood assessment consists of determining the likelihood that wild susceptible fish would become infected with *A. salmonicida* 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 *A. salmonicida* are present on one or more farms in the Discovery Islands area?

3.1.2 Considerations

Factors contributing to the detection of *A. salmonicida* infections on Atlantic Salmon farms are based both on regulatory requirements and industry practices.

3.1.2.1 Regulatory requirements

3.1.2.1.1 Licensing requirements

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 licences 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 (Wade, 2017), 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.

3.1.2.1.2 Fish Health Audit and Surveillance Program

Through the Fish Health Audit and Surveillance Program (FHASP), samples are collected from recently dead fish 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).

Under the FHASP, furunculosis is diagnosed in an Atlantic Salmon population when the site is under treatment for the disease or when sampled fish show septicaemia with characteristic histologic lesions, with isolation or identification of the causative bacterium from tissues, and population level losses attributed to the disease (I. Keith, DFO, pers. comm., 2018).

Boily et al. (2019) summarized audit-based detections of *A. salmonicida* and farm-level furunculosis diagnoses between 2002 and 2016 in BC. Details of detections and diagnoses specific to Atlantic Salmon farms in the Discovery Islands area are included in Appendix A. Briefly:

- There were no audit-based detections of *A. salmonicida* through bacteriology or histology; and
- There were no audit-based farm-level furunculosis diagnoses.

Although the DFO FHASP is not designed to capture incidence or prevalence, detections are indicative of the presence of the pathogen and/or disease in some individuals on farms. These results indicate that no *A. salmonicida* was detected in the fish sampled.

As part of a research project, molecular evidence of *A. salmonicida* genomic DNA has been reported in audit samples collected between April 2011 and December 2013 from Atlantic Salmon farms in BC including farms in Fish Health Surveillance Zones 3.2 and 3.3 (Laurin et al., 2019).

3.1.2.1.3 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 autumn 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 and the industry provided the FHEs that occurred on Atlantic Salmon farms in the Discovery Islands area during this period to inform this assessment.

A total of six FHEs attributed to furunculosis were reported on a total of six Atlantic Salmon farms in the Discovery Islands area between 2002 and 2017 (Appendix B).

3.1.2.1.4 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).

No mortality events attributed to furunculosis, or to any other infectious diseases, were reported on Atlantic Salmon farms in the Discovery Islands area between 2011 and 2017 (DFO, 2018b). Mortality event reporting was required prior to 2011 but details and reports are not available.

3.1.2.1.5 Regulation of movement of live fish

The movement of live aquatic animals is regulated by the Canadian Food Inspection Agency (CFIA) and DFO. Movement control measures contribute to prevention of the introduction of pathogens on marine farm sites and are hence relevant to determine the likelihood of *A. salmonicida* infection on Atlantic Salmon farms.

CFIA grants permits for Aquatic Animal Domestic Movements to contain certain aquatic animal reportable diseases. As furunculosis is not a reportable disease for finfish in Canada (CFIA, 2018a), this form of movement control is not further considered.

DFO grants Introduction and Transfer licences 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 in the province. For the aquaculture industry, the ITC assesses the health of fish to be transferred which includes the diseases and causative agents included in Appendix III of the Marine Finfish Aquaculture Licence under the Fisheries Act (Diseases of regional, national or international concern) along with any other concern that may arise during the assessment, which would include clinical signs of furunculosis. 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 if there are any other concerns, the ITC can either recommend that the transfer should not happen, or they can work with the applicant to ensure the transfer is carried out in a safe manner (Mark Higgins, DFO, Pacific Biological Station, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, pers. comm., 2018). Licences are required for every transfer.

As a condition of a marine aquaculture licence, companies are required to have SOPs to address the movement of fish between facilities (DFO, 2015; Wade, 2017).

3.1.2.2 Industry practices

Three companies rear Atlantic Salmon on marine sites in the Discovery Islands area: Cermaq Canada, Grieg Seafood and Mowi Canada West. Refer to Wade (2017) for an overview of health management practices on Atlantic Salmon farms in BC.

3.1.2.2.1 Surveillance and testing

Every active marine production site is monitored daily by on-site trained staff for syndromic surveillance during which mortalities are removed and classified. Staff are required to alert the veterinarian if there are any signs of particular pathogens or diseases (Wade, 2017). 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 active Cermaq Canada 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). In addition to gross lesion scoring of all major organ systems, full histology on three of these fish plus a pool of kidney tissue (up to five fish) is frozen for potential submission by the veterinarian based on either mortality trends or on-site observations. For the first six weeks after transfer to marine production sites, six fresh silvers per cage are sampled every two weeks for bacteriology testing. Finally, at least once per quarter, a pool of kidney tissue is submitted for polymerase chain reaction (PCR) testing (for infectious hematopoietic necrosis virus (IHNV), viral hemorrhagic septicaemia virus (VHSV), and *Piscirickettsia salmonis*) and three fish are submitted for full histology examination (B. Milligan, Cermaq Canada, 203-919 Island Highway, Campbell River, BC, Canada V9W 2C2, pers. comm., 2018).

In addition to daily monitoring, every active Grieg Seafood 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, 1180 Ironwood St, Campbell River, BC V9W 5P7, pers. comm., 2018).

In addition to daily monitoring, every active Mowi Canada West 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, 124-1334 Island Highway, Campbell River, BC V9W 8C9, pers. comm., 2018).

Bacteriological screening and testing by the industry are not limited to routine surveillance. Other reasons for bacteriological testing include research and development, investigation of mortality events, and when fresh mortalities show gross lesions compatible with a systemic condition of unknown etiology, or as required by the veterinarian and the fish health team. Bacteriology is done in-house using culture-based methods for bacterial isolation.

Pathogen identification is based on subcultures and additional tests performed in-house or by an external diagnostic laboratory.

3.1.2.2.2 Movement of live fish

With the exception of one farm, smolts are not stocked directly from freshwater to marine sites in the Discovery Islands area due to the risk of infection from *Kudoa* sp., a parasite of marine fishes (Wade, 2017). Direct stocking occurs at Raza where *Kudoa* sp. has not been an issue (D. New, Cermaq Canada, 203-919 Island Highway, Campbell River, BC, Canada V9W 2C2, pers. comm., 2018).

In BC, any movement of live fish to fish-rearing facilities requires an Introductions and Transfers licence under section 56 of the *Fisheries (General) Regulations*. The decision to issue a licence is based on the recommendations of the ITC. This includes consideration of the results of the pre-transfer health assessments conducted according to company-specific best practices:

- Six to eight weeks prior to every live fish transfer, Cermaq Canada conducts bacteriology (n=30) and PCR for IHNV, VHSV and piscine orthoreovirus (in pools of five fish) on 30 moribund fish. PCR is also conducted for detection of infectious pancreatic necrosis virus (IPNV), infectious salmon anemia virus (ISAV), *Renibacterium salmoninarum* prior to transfers from freshwater to seawater facilities, and for *Piscirickettsia salmonis* prior to transfers from seawater to seawater facilities.
- Three weeks prior to live fish transfers, Grieg Seafood conducts general necropsy (n=30), bacteriology (n=30) and PCR on 30 fish (six pools of five fish) from the subpopulation (P. Whittaker and T. Hewison, Grieg Seafood, pers. comm., 2018).
- Prior to any live fish transfer, Mowi Canada West conducts bacteriology (n=20), virology (four pools of five fish) and histology (n=5 to 10) testing on 20 randomly selected silver fish (D. Morrison, Mowi Canada West, pers. comm., 2018).

3.1.2.2.3 Vaccination

In BC, vaccination of Atlantic Salmon is not a condition of licence and is therefore voluntary (DFO, 2015; Wade, 2017). In Canada, three vaccines are currently authorized for use against furunculosis in salmonids grown in Canada (CFIA, 2018b). Vaccine efficacy data are not available.

Cermaq Canada, Grieg Seafood and Mowi Canada West have always and continue to vaccinate all Atlantic Salmon in hatcheries with Forte Micro®, or a commercial equivalent, to prevent furunculosis and vibriosis. The Forte Micro® vaccine is considered efficacious in production fish (P. Whittaker and T. Hewison, Grieg Seafood, pers. comm., 2018; D. Morrison, Mowi Canada West, pers. comm., 2018). However, despite 100% vaccine coverage, furunculosis may still develop under stress conditions (i.e., handling and transfer between sites) if carriers were present in the population prior to vaccination (B. Milligan, Cermaq Canada, pers. comm., 2018).

3.1.2.2.4 Treatment

Treatment options for furunculosis in hatcheries and marine production sites can vary among aquaculture companies. Treatment with in-feed antibiotics is efficacious at reducing furunculosis related mortalities; however, carrier fish may still be present in the population after treatment.

Cermaq Canada, Grieg Seafood and Mowi Canada West may treat fish with in-feed oxytetracycline for 10 to 14 days, florfenicol for 10 days, sulfadiazine/trimethroprim for 10 days or sulfadimethoxine/ormetoprim for five days when signs of furunculosis are present in Atlantic Salmon on marine production sites. The choice of antibiotic depends on the sensitivity of the organism and other factors. The length of the treatment is dependent on the prescribed drug, veterinarian judgement and size of the fish. Grieg Seafood and Mowi Canada West may treat or cull infected stocks in hatcheries, followed by disinfection and cleaning of the rearing units (P. Whittaker and T. Hewison, Grieg Seafood, pers. comm., 2018; D. Morrison, Mowi Canada West, pers. comm., 2018).

3.1.2.3 Detections by the industry

Based on the results of observations and testing conducted by the industry on Atlantic Salmon farms in the Discovery Islands area between 2011 and 2017, *A. salmonicida* was detected in at least one fish in 3.9% of site visits with testing for the bacterium. Overall, *A. salmonicida* was detected in at least one fish in each of two farms in 2013, one farm in 2014, and one farm in 2017. Both typical and atypical strains have been reported by the industry. Refer to Appendix C for details.

3.1.2.4 Summary of *Aeromonas salmonicida* and furunculosis on Atlantic Salmon farms in the Discovery Islands area

In this risk assessment, evidence of *A. salmonicida* infections and/or furunculosis refers to fish sampled during routine screenings by the industry, through regulatory programs, fish health events, or any other diagnostic workups on the farms with (i) samples positive for *A. salmonicida* identified through bacteriological cultures or PCR, or (ii) furunculosis identified through histology.

Table 7 summarizes data related to Atlantic Salmon farms in the Discovery Islands area with evidence of *A. salmonicida* infections and/or furunculosis signs and diagnoses by year between 2002 and 2017. Data were collated separately from different regulatory reporting requirements (results from the FHASP; FHEs and mortality events reported by the industry to DFO) and from industry testing and diagnoses. Therefore, an infection on the same farm may be captured in more than one category so number of farms cannot simply be added between categories or years.

It is acknowledged that the presence of a pathogen in an individual fish does not always result in clinical signs or disease in a population. *Aeromonas salmonicida* has not been detected through the audits, but the industry has detected *A. salmonicida* and reported on-farm treatments for furunculosis.

Overall, *A. salmonicida* has been reported in six years (2003, 2009, 2010, 2013, 2014, and 2017) on a total of seven different farms between 2002 and 2017. Treatment for furunculosis, including FHEs, was reported on six different farms.

Table 7. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of Aeromonas salmonicida *infection and/or furunculosis summarized by year. Data include results from industry testing by bacterial culture and/or polymerase chain reaction (PCR) (2011-2017), results from the Fish Health Audit and Surveillance Program (FHASP) (2002-2016), fish health events (FHEs) (2002-2017) and mortality events (2011-2016) reported by the industry to Fisheries and Oceans Canada (DFO). NA: data not available. Months with evidence of* A. salmonicida *and/or furunculosis are shaded and bolded.*

Year	Number of active farms	Industry data	FHASP data			Reported to DFO by industry	
		Number of farms with at least one positive sample (culture, PCR) / total number of farms tested	Number of farms with *A. salmonicida* identified through bacteriology / total number of farms audited	Number of farms with furunculosis identified through histology / total number of farms audited	Number of farms with farm-level furunculosis diagnoses / total number of farms audited	Number of farms with FHEs attributed to furunculosis	Number of farms with mortality events attributed to furunculosis
2002	NA	NA	0/3	0/3	0/3	0	NA
2003	NA	NA	0/4	0/4	0/4	**1**	NA
2004	14	NA	0/9	0/9	0/9	0	NA
2005	15	NA	0/11	0/11	0/11	0	NA
2006	16	NA	0/12	0/12	0/12	0	NA
2007	16	NA	0/13	0/13	0/13	0	NA
2008	17	NA	0/15	0/15	0/15	0	NA
2009	18	NA	0/14	0/14	0/14	**1**	NA
2010	16	NA	0/4	0/4	0/4	**2**	NA
2011	17	0/11	0/8	0/8	0/8	0	0
2012	13	0/6	0/12	0/12	0/12	0	0
2013	8	**2 /7**	0/7	0/7	0/7	**1**	0
2014	10	**1/7**	0/8	0/8	0/8	0	0
2015	10	0/6	0/9	0/9	0/9	0	0
2016	11	0/11	0/11	0/11	0/11	0	0
2017	12	**1 /10**	NA	NA	NA	**1**	0

3.1.3 Assumptions

- Positive detection of the pathogen is evidence of infection; and
- Diagnostic results can be pooled regardless of the differences between methodologies and test performance characteristics for the purpose of indicating the occurrence of the pathogen on farms.

3.1.4 Likelihood of farm infection

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

Table 8. Factors contributing to and limiting the likelihood that farmed Atlantic Salmon infected with Aeromonas salmonicida *are present on one or more Atlantic Salmon farms in the Discovery Islands area under the current fish health management practices. FHE: fish health event; SHMP: salmonid health management plan.*

Contributing factors	Limiting factors

• Atlantic Salmon are susceptible to *A. salmonicida* infections;
• FHEs attributed to furunculosis occurred in 2003, 2009, 2010, 2013 and 2017;
• From 2002 to 2017, there is evidence of *A. salmonicida* and/or furunculosis:
  o on a total of seven Atlantic Salmon farms in the Discovery Islands area; and
  o on at least one farm in six different years (2003, 2009, 2010, 2013, 2014 and 2017); and
• Even with complete vaccine coverage, furunculosis may still develop under certain conditions, i.e., if carriers were present in the population prior to vaccination.
	• All Atlantic Salmon farming companies conduct diagnostic testing for *A. salmonicida* through bacteriology prior to any live transfer;
	• All Atlantic Salmon reared in the Discovery Islands area are vaccinated to prevent furunculosis;
	• *Aeromonas salmonicida* was not detected and furunculosis was not diagnosed at the farm level during fish health audits (2002-2017) on Atlantic Salmon farms in the Discovery Islands area; and
	• SHMP include requirements for minimizing stress during transfer, handling and harvesting (DFO, 2015).

It was concluded that, in a given year, the likelihood that farmed Atlantic Salmon infected with *A. salmonicida* are present on one or more Atlantic Salmon farms in the Discovery Islands area is **unlikely** under the current farm practices given evidence of *A. salmonicida* and/or furunculosis on farms in six of 16 years (2002 to 2017). This conclusion was made with **reasonable certainty** given abundant and robust data about screening and detections on farms from different sources and over 16 years.

3.2 RELEASE ASSESSMENT

3.2.1 Question

Assuming that Atlantic Salmon infected with *A. salmonicida* are present, what is the likelihood that any *A. salmonicida* would be released from an Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to wild fish populations?

3.2.2 Considerations

Considerations include Atlantic Salmon rearing method; shedding of *A. salmonicida* 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 pens 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 *Aeromonas salmonicida* from infected fish

Boily et al. (2019) reviewed the state of knowledge related to shedding in *A. salmonicida*-infected fish. The bacterium is shed at all stages of infection including carriers (Pérez et al., 1996; Hiney and Olivier, 1999; Ogut, 2001), clinically infected fish (Rose et al., 1989; Ogut, 2001) and dead hosts (McCarthy, 1977; Rose et al., 1989; Enger et al., 1992; Pérez et al., 1996). Shedding rates have been estimated under laboratory conditions in both *A. salmonicida*-infected Atlantic Salmon (Rose et al., 1989) and Rainbow Trout (*O. mykiss*) (McCarthy, 1977; Pérez et al., 1996).

Of greatest relevance to this risk assessment are shedding rates in seawater from *A. salmonicida*-infected Atlantic Salmon. Rose et al. (1989) challenged Atlantic Salmon (25.8 g, n=6) with *A. salmonicida* in a seawater bath immersion and reported median shedding rates of 1.7×10^6 cfu per fish per hour in freshly dead fish. The same authors also injected *A. salmonicida* in Atlantic Salmon in seawater and reported median shedding rates of 1.3×10^6 cfu per fish per hour in 23 g live fish (n=4) one day before death and 5.4×10^7 cfu per fish per hour in 1200 g fish (n=2) on day of death (range: 9.0×10^6 to 6.4×10^8 cfu per fish per hour).

To date, shedding rates in healthy carriers have not been reported.

3.2.2.3 Fish health management practices

As a condition of licence, all companies must comply with the SHMP which includes biosecurity measures to maintain fish health, prevent pathogen entry and limit the spread of diseases on farm (DFO, 2015), some of which will affect the likelihood of pathogens to be released from an infected farm.

The 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 that a SOP is required and a description of the goal, 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 are in place to control vessel movement (Wade, 2017). All companies use Virkon® Aquatic, a broad-spectrum disinfectant (Wade, 2017) which was reported to be effective against furunculosis (Fraser et al., 2006).

Compliance with these elements is determined through the FHASP. On average, less than one deficiency per audit has been reported between 2011 and 2015 on Atlantic Salmon farms in the Discovery Islands area (Wade, 2017). Most reported deficiencies were related to sea lice protocols, carcass retrieval protocol or incomplete record keeping. See Wade (2017) for a detailed breakdown of deficiencies by category.

3.2.3 Assumptions

- Atlantic Salmon infected with *A. salmonicida* are present on at least one farm; and
- Biocontainment measures are effective against *A. salmonicida*.

3.2.4 Likelihood of release

Table 9 presents the main factors contributing to and limiting the likelihood of release. These factors were used to determine the likelihood and uncertainty rankings based on definitions in Table 2, Table 5 and Table 6.

Table 9. Factors contributing to and limiting the likelihood that Aeromonas salmonicida *will be released from infected and/or diseased Atlantic Salmon on farms in the Discovery Islands area under the current farm practices.*

Contributing factors	Limiting factors
• Infected Atlantic Salmon in seawater can shed *A. salmonicida* (Rose et al., 1989); • The bacterium can be shed at most stages of infection including carriers or subclinical infection, diseased and dead fish; and • Atlantic Salmon in the Discovery Islands area are reared in net pens allowing pathogens, including *A. salmonicida*, to be released from 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 (Wade, 2017); • 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 (Wade, 2017); • Protocols are in place to minimize predators and wildlife access (Wade, 2017); • 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 (Wade, 2017); • Protocols are in place for cleaning, disinfecting and transferring large and submerged equipment among sites (Wade, 2017); • Biosecurity measures are in place to control vessel movement (Wade, 2017); and • On average, less than one operational deficiency per audit has been reported between 2011 and 2015 on Atlantic Salmon farms in the Discovery Islands area (Wade, 2017).

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

3.2.4.1 Release through infected farmed Atlantic Salmon

It was concluded that the likelihood that *A. salmonicida* would be released from an Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to wild fish populations through infected Atlantic Salmon is **extremely likely** under the current fish health management practices given rearing in net pens and evidence that infected Atlantic Salmon can shed the bacterium. This conclusion was made with **high certainty** given abundant, robust and peer-reviewed evidence of shedding of *A. salmonicida* from infected salmonids.

3.2.4.2 Release through vectors and fomites

It was concluded that the likelihood that *A. salmonicida* 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 fish health management practices. This conclusion was made with **reasonable certainty** given that the relevant biosecurity practices are part of licence requirements and therefore specified in SHMP and relevant SOPs and there are low levels of operational deficiencies that could affect fish health on Atlantic Salmon farms in the Discovery Islands area.

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 *A. salmonicida* would be released from an Atlantic Salmon farm should it become infected.

3.3 EXPOSURE ASSESSMENT

3.3.1 Question

Assuming that *A. salmonicida* has been released from at least one Atlantic Salmon farm in the Discovery Islands area, what is the likelihood that at least one susceptible fish would be exposed to *A. salmonicida* 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., 2015).

Considerations include susceptible species; relative size and volume of Atlantic Salmon farms; occurrence of susceptible species in the Discovery Islands area; survival of *A. salmonicida* in the marine environment; and timing of *A. salmonicida* infections on Atlantic Salmon farms in the Discovery Islands area.

3.3.2.1 Susceptible species

All salmonid species are considered susceptible to *A. salmonicida* infections and furunculosis (Kent, 2011) Although susceptibility to infection is reported to be highest in Atlantic Salmon and Brown Trout (*S. trutta*) and lowest in Rainbow Trout *(O. mykiss)* (McCarthy, 1977; Cipriano and Heartwell, 1986; Bernoth, 1997; Hiney and Olivier, 1999; Roberts, 2012), no studies have compared the relative susceptibility of Pacific salmon species with that of Atlantic Salmon in freshwater or seawater (Boily et al., 2019). Pacific salmon species are therefore considered to be equally susceptible to *A. salmonicida* infection and disease in this risk assessment. Refer to Boily et al. (2019) for additional details including susceptible non-salmonid species that are not included in this risk assessment.

Boily et al. (2019) also reviewed studies reporting infections with *A. salmonicida* and development of disease in different life stages, and concluded that although infection and disease can occur in all life stages there are insufficient data to assign different susceptibilities to the different life history stages of Pacific salmon.

In addition to Sockeye Salmon, other susceptible Pacific salmon species considered in this risk assessment are Chinook (*O. tshawytscha*), Chum (*O. keta*), Coho (*O. kisutch*) and Pink (*O. gorbuscha*) salmon.

3.3.2.2 Atlantic Salmon farm size and volume

Atlantic Salmon farms operating in the Discovery Islands area occupy 0.007% of the area and 0.0008% of the volume of the overall area (Mimeault et al., 2017). Considering that channel width in the Discovery Islands area varies between approximately 850 and 3,200 m, 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.

3.3.2.3 Fraser River Sockeye Salmon in Discovery Islands area

3.3.2.3.1 Juveniles

Juvenile Sockeye Salmon have been found in the Discovery Islands area in a number of different locations in several studies throughout many years (Levings and Kotyk, 1983; Brown et al., 1984; Groot and Cooke, 1987; Neville et al., 2013; Beacham et al., 2014; Johnson, 2016; Neville et al., 2016). Based on those studies, Grant et al. (2018) summarized that juvenile lake-type Fraser River Sockeye Salmon migrate through the Discovery Islands from mid-May to mid-July, with peak catches in early-to-mid June.

Out of the six years with evidence of *A. salmonicida* and/or furunculosis on Atlantic Salmon farms since 2002, three years reported evidence of the pathogen during the months of May to July (Table 10 and Table 11).

3.3.2.3.2 Adults

Returning adult Sockeye Salmon have been caught in 98% of the Pacific Salmon Commission test fisheries sets conducted in the Discovery Islands area between 2000 and 2015 (Grant et al., 2018) providing evidence of their presence in the Discovery Islands from mid-July to mid-September. Then, by combining when the earliest and latest returning adult Sockeye Salmon migrate past in the Lower Fraser River at Mission, BC (located 60 km upstream of the Fraser River outlet to the southern Strait of Georgia) with the average swimming speed and the distance from the northwestern and southwestern limits of the Discovery Islands area, Grant et al. (2018) estimated that returning adult Fraser River Sockeye Salmon migrate through the Discovery Islands area from June to October.

Out of the six years with evidence of *A. salmonicida* and/or furunculosis on Atlantic Salmon farms since 2002, six years included evidence of the pathogen during the months of June to October (Table 10 and Table 11).

3.3.2.4 Other Pacific salmon species in the Discovery Islands area

This section summarises available information about the presence of other Pacific salmon species in the Discovery Islands area.

3.3.2.4.1 Juveniles

Levings and Kotyk (1983) reported catches of juvenile salmon during two boat trawls conducted in March to August 1982 and in June 1983 in the Discovery Islands area and adjacent channels. Chum Salmon dominated catches, and in 1982, both Chum and Pink salmon peaked in abundance in late June. Chinook and Coho were less abundant while Sockeye Salmon and steelhead trout (*O. mykiss*) were uncommon (Levings and Kotyk, 1983). Only two Sockeye Salmon were reported in this survey. Based on 1982 results, juvenile Pacific salmon (Chinook, Chum, Coho and Pink salmon) were mainly caught from late-May to mid-July, but some fish were caught from late-March (Pink Salmon, n=7) to late-August (Chinook Salmon, n=1 and Coho Salmon, n=1).

Brown et al. (1987) compiled juvenile Pacific salmon beach seine catches from several estuarine, transition and marine sites along the Discovery Passage from March 1982 to August

1986[1]. Catches varied over the years but Chinook Salmon were mainly caught between May and mid-August (all catches between mid-March and early-September); Chum Salmon were mainly caught between mid-April and mid-July (all catches between mid-March and late-August); Coho Salmon were mainly caught between mid-May and mid-June (all catches between mid-April and late-August); and Pink Salmon were mainly caught between mid-April and early-July (all catches between mid-March and mid-August). Based on this study, juveniles Chinook, Chum, Coho or Pink salmon were caught from mid-March to early-September.

Bravender et al. (1999) sampled for juvenile salmon by beach and purse seine in Discovery Passage in 1996. Samples were collected from May 2nd to July 17th. Juvenile Pink and Chum salmon were abundant in beach seines outside of the marina throughout May. They remained present at much lower numbers until early (Pink Salmon) and mid (Chum Salmon) July (Bravender et al., 1999). Juvenile Chinook Salmon were collected from early May to mid-July with the majority caught from May through mid-June. Small numbers of juvenile Coho Salmon were caught from late May through mid-July. No Sockeye Salmon were caught in this study.

Echosounders were deployed in Okisollo Channel from mid-March to mid-late September in 2015 and 2016 (Rousseau et al., 2017). Based on acoustic data, in 2015, juvenile salmon were present at Site 1 (Venture Point, Okisollo Chanel) from mid-May through mid-July after which time there is little acoustic signal that can be associated with juvenile Pacific salmon. In 2016 there was consistently high juvenile Pacific salmon signals from mid-May to mid-June but unlike 2015 there was little signal from mid-June through to the end of the deployment (mid-September). In both years, most juvenile Pacific salmon occurred in the top five to six meters (Rousseau et al., 2017).

3.3.2.4.2 Adults

Adult Chinook, Chum, Coho, Pink and Sockeye salmon have been caught in Pacific Salmon Commission test fisheries conducted at the Lower Johnstone Strait location from July to September (2000-2015) (Grant et al., 2018). Daily catch-per-unit-effort (CPUE) (average count per set ± SD) of Sockeye (7.4 ± 8.3 to 2544.2 ± 3177.0) and Pink (7.4 ± 10.7 to 1416.7 ± 1665.6) salmon was greater than that of Chinook (0.6 ± 0.6 to 1.3 ± 1.2), Chum (0.3 ± 0.4 to 5.8 ± 12.2) and Coho (0.2 ± 0.2 to 2.6 ± 6.3) salmon in all years. Although steelhead trout were occasionally reported, the average CPUE remained at zero (reviewed in Grant et al. (2018)). Manzer (1955) also reported catches of returning Pink Salmon in the Discovery Passage from July to September (and very low numbers in October).

3.3.2.4.3 Summary

Overall, the above Pacific salmon species can be found in the Discovery Islands area from mid-March to October. Additionally, given that Chinook Salmon have a tendency to reside in coastal waters for longer periods than other species (Zetterberg and Carter, 2010; Zetterberg et al., 2012), it is reasonable to assume that they could be present in the Discovery Islands area at any time of the year.

Therefore, there is temporal overlap between the five anadromous Pacific salmon species and evidence of *A. salmonicida* on Atlantic Salmon farms in the Discovery Islands (Table 10 and Table 11).

[1] Refer to Brown et al. (1987) for details on sampling times. Briefly, trips were made at least once each month from March to December in 1982; from January to December in 1983; from January to September in 1984; in January and from March to August in 1985; and from April to August in 1986.

3.3.2.5 *Aeromonas salmonicida* survival in the marine environment

Boily et al. (2019) reviewed the state of knowledge about the survival of *A. salmonicida* in the environment. Studies most relevant to survival in the marine environment are reported here.

The bacterium has been documented to survive in seawater (McCarthy, 1977; Rose, 1990; Rose et al., 1990b; Effendi and Austin, 1991; Effendi and Austin, 1994) Culture studies conducted in non-sterile seawater report that survival of *A. salmonicida* varies between approximately two and 26 days (McCarthy, 1977; Rose, 1990; Rose et al., 1990b; Effendi and Austin, 1994) depending on experimental conditions, including temperature and salinity.

Aeromonas salmonicida can adhere to a variety of substrates such as wood, sand, mud and algae in the marine environment (Effendi and Austin, 1994) Under experimental conditions, survival of *A. salmonicida* attached to these substrates was found to vary between approximately six and at least 14 days in non-sterile seawater at 15°C (Effendi and Austin, 1994).

Additionally, *A. salmonicida* has been found to survive in sediments and can be transported through feces and carcasses of infected fish (Enger and Thorsen, 1992). Culture studies conducted with sediments in non-sterile seawater report that survival of *A. salmonicida* varies between approximately five and 11 days at 15°C (Rose et al., 1990b; Effendi and Austin, 1994).

3.3.2.6 Timing of *Aeromonas salmonicida* and furunculosis on Atlantic Salmon farms in Discovery Islands area

Table 10 summarizes evidence of *A. salmonicida* infection and/or furunculosis by month between 2002 and 2017 on Atlantic Salmon farms in the Discovery Islands area:

- based on industry surveillance and screening results (2011-2017), *A. salmonicida* was detected through culture or PCR in at least one fish on at least one farm in the months of February, June, August, September and October;
- there were no audit-based detections of *A. salmonicida* and consequently no audit-based farm-level furunculosis diagnoses (2002-2016);
- FHEs attributed to furunculosis were reported on one farm in each of January, February, April to June, and October (2002-2016); and
- no mortality events (2011-2017) were attributed to furunculosis.

Overall, based on all sources of data between 2002 and 2017, *A. salmonicida* was reported on at least one Atlantic Salmon farm in the Discovery Islands area in all months except March, July, November and December. No seasonal patterns of infection or disease could be found. At least four of the six FHEs attributed to furunculosis were reported within three months after transfer to marine site in the Discovery Islands area. Table 11 summarizes all evidence of *A. salmonicida* and/or furunculosis per year and month reported on Atlantic Salmon farms located in the Discovery Islands area.

Table 10. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of Aeromonas salmonicida *infection and/or furunculosis summarized by month. The "X" indicates evidence of presence of Pacific salmon species in a given month; CS Indicates assumed presence of Chinook Salmon. Data include results from industry testing by bacterial culture and and/or polymerase chain reaction (PCR) (2011-2017), results from the Fish Health Audit and Surveillance Program (2002-2016), fish health events (FHEs) (2002-2017) and mortality events (2011-2017) reported by the industry to Fisheries and Oceans Canada (DFO). Letters on the first row of the table represent months of the year from January to December. Months with wild fish in the Discovery Islands area and months with evidence of* A. salmonicida *and/or furunculosis are shaded and bolded.*

Occurrence in the Discovery Islands area	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Lake-type juvenile Fraser River Sockeye Salmon					X	X	X					
Returning adult Fraser River Sockeye Salmon						X	X	X	X	X		
Other Pacific salmon species	CS	CS	X	X	X	X	X	X	X	X	CS	CS
Evidence of *A. salmonicida* and/or furunculosis	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Number of farms with at least one positive sample / total number of farms tested (industry data)	0/10	**1/7**	0/10	0/9	0/6	**2/9**	0/8	**1/9**	**1/8**	**1/10**	0/10	0/12
Number of farms with furunculosis identified through histology / total number of farms audited (audit data)	0/14	0/11	0/5	0/14	0/10	0/10	0/12	0/14	0/11	0/16	0/13	0/10
Number of farms with *A. salmonicida* identified through bacteriology / total number of farms audited (audit data)	0/14	0/11	0/5	0/14	0/10	0/10	0/12	0/14	0/11	0/16	0/13	0/10
Number of farms with farm-level furunculosis diagnoses / total number of farms audited (audit data)	0/14	0/11	0/5	0/14	0/10	0/10	0/12	0/14	0/11	0/16	0/13	0/10
Number of farms with FHEs attributed to furunculosis (reported by industry)	**1**	**1**	0	**1**	**1**	**1**	0	0	0	**1**	0	0
No. of farms with mortality events attributed to furunculosis (reported by industry)	0	0	0	0	0	0	0	0	0	0	0	0

Table 11. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of Aeromonas salmonicida *and/or furunculosis summarized per year and month. Data includes results from tests conducted by industry (2011-2017), Fish Health Audit and Surveillance Program (2002-2016), fish health events (2002-2017) and/or mortality events (2002-2017). Between 2004 and 2017, the number of active Atlantic Salmon farms varied between three and 17 in a given month (number of active farms not available for 2002 and 2003). Months with evidence of* A. salmonicida *and/or furunculosis are shaded and bolded.*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	0	0	0	0	0	0	0	0	0	0	0	0
2003	0	0	0	**1**	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	**1**	0	0	0	0	0	0	0
2010	**1**	**1**	0	0	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0	0	0	0	0
2013	0	**1**	0	0	0	**1**	0	0	0	0	0	0
2014	0	0	0	0	0	**1**	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0

3.3.3 Assumptions

- *Aeromonas salmonicida* has been released from at least one Atlantic Salmon farm operating in the Discovery Islands area;
- Positive detections of *A. salmonicida* are evidence that the pathogen is present in sampled fish;
- *Aeromonas salmonicida*-infected fish are shedding the bacterium;
- Evidence of shedding is limited to the months with evidence of infection or disease 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 12 presents the main factors contributing to and limiting the likelihood of Pacific salmon (sp.) to be exposed to *A. salmonicida* attributed to Atlantic Salmon farm(s) in the Discovery Islands area. These factors were used to determine the likelihood and uncertainty rankings based on definitions in Table 2, Table 5 and Table 6.

Table 12. Factors contributing to and limiting the likelihood that Fraser River Sockeye Salmon and other Pacific salmon species would be exposed to Aeromonas salmonicida *released from infected/diseased Atlantic Salmon farm(s) in the Discovery Islands area under the current fish health management practices.*

Contributing factors	Limiting factors
• Millions of juvenile and adult Fraser River Sockeye Salmon migrate through the Discovery Islands area every year (reviewed in Grant et al. (2018)); • Fraser River Sockeye Salmon, as well as the other Pacific salmon species, overlap in time and space with occurrences of *A. salmonicida* on Atlantic Salmon farms in the Discovery Islands area; • Culture studies conducted in non-sterile seawater reported *A. salmonicida* to survive for from three to 26 days (McCarthy, 1977; Rose et al., 1990b; Effendi and Austin, 1991; Effendi and Austin, 1994); and • Hydrodynamic transmission of *A. salmonicida* in seawater has been reported between cages on an Atlantic Salmon farm in Ireland (Smith et al., 1982) and suggested through particle tracking modeling in an hypothetical sea loch (Rose, 1990).	• Atlantic Salmon farms are not found in all channels of the Discovery Islands area; • Atlantic Salmon farms occupy a relatively small surface area and volume of the Discovery Islands area (Mimeault et al., 2017); and • Fish health audits have never diagnosed furunculosis at the farm level, or reported furunculosis on individual fish through histology, nor detected *A. salmonicida* in sampled carcasses on Atlantic Salmon farms in the Discovery Islands area (DFO, 2018c).

This risk assessment considered three exposure groups (juvenile Fraser River Sockeye Salmon, adult Fraser River Sockeye Salmon and other susceptible species) and one exposure route (waterborne exposure).

The likelihood that at least one susceptible fish could be exposed to *A. salmonicida* attributable to Atlantic Salmon farms was informed by the number of years with evidence of *A. salmonicida* and/or furunculosis while susceptible fish are present in the area, divided by the number of years with evidence of *A. salmonicida* and/or furunculosis (six years, see Table 11).

3.3.4.1 Exposure of juvenile Fraser River Sockeye Salmon

It was concluded that the likelihood that at least one juvenile Fraser River Sockeye Salmon could be exposed to *A. salmonicida* attributable to Atlantic Salmon farms located in the Discovery Islands area through waterborne exposure is **likely** under the current fish health management practices given their temporal overlap in the Discovery Islands area with reports of *A. salmonicida* on farms. Out of the six years with evidence of *A. salmonicida* and/or furunculosis on farms since 2002, three years had evidence between May and July which corresponds to when juvenile Fraser River Sockeye Salmon are expected to be present in the Discovery Islands area (Table 11). This conclusion was made with **reasonable certainty** given abundant and robust data documenting the presence of juvenile Sockeye Salmon in the Discovery Islands area and occurrence of *A. salmonicida* and furunculosis on Atlantic Salmon farms in the Discovery Islands area.

3.3.4.2 Exposure of adult Fraser River Sockeye Salmon

It was concluded that the likelihood that at least one adult Fraser River Sockeye Salmon could be exposed to *A. salmonicida* attributable to an Atlantic Salmon farm located in the Discovery Islands area through waterborne exposure is **likely** under the current fish health management practices given the temporal overlap in the Discovery Islands area with reports of *A. salmonicida* on farms. Out of the six years with evidence of *A. salmonicida* and/or furunculosis on farms since 2002, three years had evidence between June and October which corresponds to when adult Fraser River Sockeye Salmon are expected to be present in the Discovery Islands area (see Table 11). This conclusion was made with **reasonable certainty** given abundant and robust data documenting the presence of adult Sockeye Salmon in the Discovery Islands area and occurrence of *A. salmonicida* and furunculosis on Atlantic Salmon farms in the Discovery Islands area.

3.3.4.3 Exposure of other susceptible Pacific salmon species

It was concluded that the likelihood of at least one susceptible Pacific salmon species to be exposed to *A. salmonicida* attributable to an Atlantic Salmon farm located in the Discovery Islands area through waterborne exposure is **extremely likely** under the current fish health management practices given the temporal overlap in the Discovery Islands area as some can be present in the Discovery Islands area at any time of the year. This conclusion was made with **reasonable uncertainty** given the lack of data to support presence of these species in the Discovery Islands area throughout the year but robust and abundant data about the occurrence of *A. salmonicida* and furunculosis on Atlantic Salmon farms.

3.4 INFECTION ASSESSMENT

3.4.1 Question

Assuming that at least one susceptible wild fish has been exposed to *A. salmonicida* released from Atlantic Salmon farm(s) in the Discovery Islands area, what is the likelihood that at least one will become infected?

3.4.2 Considerations

Considerations include oceanographic and environmental conditions; minimum infectious and lethal doses; estimated duration of exposure; vaccine efficacy; mortality attributable to furunculosis on Atlantic Salmon farms; and estimated infection pressure from farms.

3.4.2.1 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). Average monthly water temperature measured 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 (Chandler et al., 2017). Water temperatures in the Discovery Islands area are suitable for the viability of *A. salmonicida* with survival ranging from approximately three to 26 days in 11 to 15°C non-sterile seawater (McCarthy, 1977; Rose et al., 1990b, a; Effendi and Austin, 1994).

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. Average monthly salinity measured 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 (Chandler et al., 2017). Salinities observed in the Discovery

Islands area are suitable for the viability of *A. salmonicida* with survival ranging from approximately two to 26 days in 23 to 35 ppt in non-sterile seawater (Lund, 1967; McCarthy, 1977; Rose et al., 1990b, a; Effendi and Austin, 1994).

3.4.2.2 Minimum infectious and lethal doses

The minimum doses necessary to cause infection or mortality with *A. salmonicida* for Sockeye Salmon have not been determined (Boily et al., 2019). In absence of minimum doses, the lowest bath concentrations and durations reported to have caused infection and mortality in Sockeye Salmon were used as proxy data for the minimum infectious and lethal doses, respectively.

McCarthy (1983) is the only laboratory study reporting the virulence of *A. salmonicida* by bath challenge in Sockeye Salmon. A 20-min immersion of fry (5.7 g, n=21) in freshwater containing 1×10^4 *A. salmonicida* (strain AS-1) cfu/mL (1×10^{10} cfu/m^3) resulted in 76% mortality. This is the lowest documented lethal dose of *A. salmonicida* in Sockeye Salmon. However, the lowest concentration of *A. salmonicida* (strain 423) reported to have caused mortality in salmonids was in Atlantic Salmon (75 to 115 g, n=10) exposed to 10^2 *A. salmonicida* cfu/mL (1×10^8 cfu/m^3) in seawater for 12 hours a day for 21 days (Rose et al., 1989). Exposure for 21 days in this study resulted in 20% mortality, while exposure for seven days did not result in mortality or infection (Rose et al., 1989). Consequently, based on available studies, the lowest infectious dose in seawater in Atlantic Salmon, can be expected to be above 10^2 *A. salmonicida* cfu/mL (1×10^8 cfu/m^3) with daily 12-h exposure for seven days.

3.4.2.3 Estimated duration of exposure

The potential duration that a susceptible fish species would be exposed to *A. salmonicida* released from an Atlantic Salmon farm in the Discovery Islands area depends on the: (i) time a susceptible fish spends in the area; and (ii) duration of *A. salmonicida* infection and furunculosis on Atlantic Salmon farms in this area.

3.4.2.3.1 Time susceptible species spend in the Discovery Islands area

Grant et al. (2018) estimated the residence time of Sockeye Salmon in the Discovery Islands area to be five to 14 days for a juvenile and three days for an adult. Atlantic Salmon farms in the Discovery Islands area are located in channels within a portion of the total. The total length of the Discovery Islands area is approximately 140 km, with the farms being located over approximately 75 km of this length. Assuming a constant migration speed and unidirectional movement, Mimeault et al. (2017) then estimated that juveniles could encounter farm(s) over three to eight days and returning adults over two days on their migration through the Discovery Islands area.

In a telemetry study conducted in 2017, the median travel time of juvenile Fraser River Sockeye Salmon (primarily from Chilko Lake) through Hoskyn and Okisollo channels (Figure 1) was approximately 30 hours and travel time from the eastern to the western end of the Okisollo Channel was approximately six hours (Rechisky et al., 2018). In the same study, receivers were also deployed at two fallowed salmon farms to measure Sockeye Salmon exposure time to a region with salmon farms. The median time that juvenile Sockeye Salmon spent near individual salmon farms was approximately 4.5 minutes suggesting short duration of exposure time to fallowed farms (Rechisky et al., 2018).

To date, the residence time around salmon farms in the Discovery Islands area of the other Pacific salmon species is unknown.

3.4.2.3.2 *Duration of* Aeromonas salmonicida *infection and furunculosis on Atlantic Salmon farms in the Discovery Islands area*

Although fish infected with *A. salmonicida* or diagnosed with furunculosis have been found on Atlantic Salmon farms in the Discovery Islands area, there are no estimates of prevalence of *A. salmonicida* infection in the population. Duration of treatment for furunculosis on Atlantic Salmon farms varies between 10 to 14 days.

3.4.2.4 Vaccine efficacy

Forte Micro®, or commercial equivalent, is the primary commercial vaccine used on Atlantic Salmon farms in BC to prevent furunculosis in salmonids. Although no efficacy data are available, Forte Micro® is considered to be efficacious by companies operating in the Discovery Islands area (Boily et al., 2019). However, despite 100% vaccine coverage of Atlantic Salmon in hatcheries, furunculosis may still develop under stress conditions (i.e., handling, transfer between sites) if carriers were already present in the population prior to vaccination, or immune competency is compromised (e.g., stress) or vaccine is not fully protective. As summarized in Boily et al. (2019), injectable formulations prepared from whole *A. salmonicida* bacterin with an oil-based adjuvant are very efficacious but cannot be delivered to very small fish (Midtlyng, 1997; USDA, 2014). As a consequence, young salmon exposed to *A. salmonicida* at the hatchery can acquire the infection before vaccination and are at risk of developing furunculosis, or they may become covertly infected and carry the pathogen when transferred to their marine grow-out sites (Munro and Waddell, 1984; Hiney, 1995).

3.4.2.5 Mortality attributable to furunculosis on Atlantic Salmon farms in Discovery Islands area

Mortality attributable to furunculosis on Atlantic Salmon farms was estimated based on data provided by the industry. Daily mortality and cause of mortality at the net-pen level for three months prior to the first day of the and up to at least one month after the end of treatment were used.

Between 2002 and 2017, a total of six FHEs attributed to furunculosis were reported on Atlantic Salmon farms in the Discovery Islands area (Table 7). Industry provided data for the last five FHEs attributed to furunculosis (mortality data were not available for event reported prior to 2009). The average daily mortality attributed to furunculosis at the farm level during FHEs was 0.1% or less in all instances except one in which the average daily mortality attributable to furunculosis was 0.21% over an 11-day period.

3.4.2.6 Estimated *Aeromonas salmonicida* infection pressure from Atlantic Salmon farms

Estimating the potential waterborne concentration of *A. salmonicida* on a farm during a furunculosis outbreak requires an estimate of the number of infected fish during an outbreak, the bacterial shedding rate, the shedding duration and the farm volume.

A precise estimate of the prevalence of *A. salmonicida* on an infected Atlantic Salmon farm is difficult to determine for several reasons. First, samples are usually collected from a small number of recently dead fish on an as needed basis as determined by the professional judgement of the veterinarian and/or fish health team. Therefore, sampled fish are not representative of the population. Second, freedom from clinical furunculosis cannot be taken as evidence of absence of *A. salmonicida* because healthy carriers may be present. Finally, although fish are vaccinated against the disease, occasional detections of *A. salmonicida* by culture indicate the bacterium can still be present, yet, likely at low levels.

As furunculosis is a stress-induced disease and given that FHEs attributed to furunculosis on Atlantic Salmon farms in the Discovery Islands area were reported within three months after transfer, the average daily mortality rate attributed to the disease was used as a proxy for the prevalence in the population. Acknowledging that this approach does not account for potential additional healthy carriers, a worst-case approach was taken in estimating the infection pressure based on the highest average daily mortality attributable to the disease during a FHE and high shedding rates based on injected fish.

The infection pressure, or estimated waterborne concentration attributable to farms, was estimated in the net pens (maximum infection pressure) and in dispersed plumes.

3.4.2.6.1 Waterborne concentration in net pens

The *A. salmonicida* waterborne concentration over 24 hours was estimated based on the highest average mortality reported on Atlantic Salmon farms during a FHE, median bacterial shedding rate reported in dead Atlantic Salmon, and farm volume which can be represented as follow:

$$[A. salmonicida] = \frac{Furunculosis\ mortality\ on\ farms\ x\ \ Shedding\ rate\ x\ Time\ period}{Volume\ of\ farm\ net\ pens}$$

Atlantic Salmon farms in operation between January 2013 and June 2018 had in average 514,000 fish per farm (maximum 781,000) (data provided by DFO Aquaculture Management). Data prior to January 2013 are not available. The average farm volume Atlantic Salmon farm in the Discovery Islands area is approximately 195,000 m^3 (Mimeault et al., 2017).

Based on an average daily mortality attributed to furunculosis of 0.21% (see section 3.4.2.4) and a shedding rate of 5.4 x 10^7 cfu per fish per hour (see section 3.2.2.2), the waterborne concentration of *A. salmonicida* after 24 hours of constant shedding was estimated to be 7.2 x 10^6 cfu/m^3. Although shedding from infected live fish would also contribute to the waterborne concentration of *A. salmonicida*, this component cannot be estimated given that farm level prevalence and shedding by subclinically infected fish are unknown. Regardless, the above estimate of 7.2 x 10^6 cfu/m^3 is considered to be an overestimate and worst-case scenario as it does not account for bacterial decay and hydrodynamic dispersion.

Boily et al. (2019) compiled decay rate constants for *A. salmonicida* in non-sterile brackish and marine environments. Applying the slowest (0.66/day) and average (2.09/day) decay rate constants to an Atlantic Salmon farm with average (514,000) or maximum (781,000) number of fish, the concentrations could theoretically reach a maximum concentration of 1.7 x 10^7 cells/m^3 on a large stocked farm within less than five days without considering hydrodynamic dispersal (Figure 5).

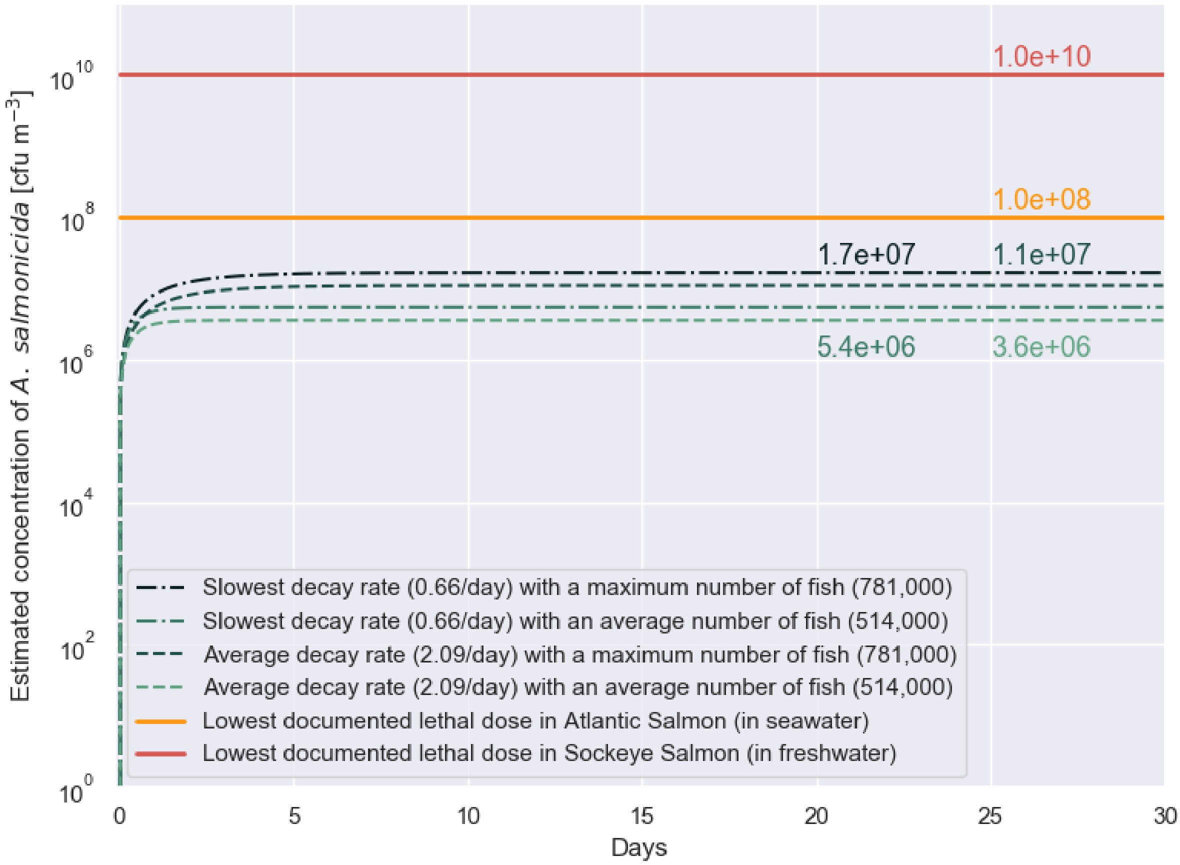

Figure 5. Estimated maximum waterborne concentration (cfu/m³) for Aeromonas salmonicida *on an infected Atlantic Salmon farm operating in the Discovery Islands area, BC. The green lines represent estimated waterborne concentrations assuming 514,000 or 781,000 fish on farm, the slowest or the average* A. salmonicida *decay rate (0.66 or 2.09 per day, respectively), a volume of 195,000 m³, constant shedding from 0.21% of the fish based on mortality attributed to furunculosis during fish health events on Atlantic Salmon in the Discovery Islands area, median shedding rates reported in dead Atlantic Salmon (5.4 x 10^7 cfu per fish per hour) and no hydrodynamic dispersal. Under the above assumptions, waterborne concentrations plateau between 3.6 x 10^6 and 1.7 x 10^7 cells/m³. The yellow line represents the lowest documented lethal dose in Atlantic Salmon in seawater (1.0 x 10^8 cells/m³ for 12 hours a day for 21 days). The red line represents the lowest documented lethal dose for Sockeye Salmon in freshwater (1.0 x 10^{10} cells/m³ for 20 minutes).*

3.4.2.6.2 Waterborne concentration in plumes

Dispersal of *A. salmonicida* from marine Atlantic Salmon farms in the Discovery Islands area was modelled using ocean circulation and dispersion, inactivation and re-infection models (Foreman et al., 2012; Foreman et al., 2015a). Appendix D details assumptions and input parameters. Briefly, the model assumes that all 18 farms were infected and releasing *A. salmonicida* particles simultaneously. Although this is not a realistic assumption, such an approach was taken to determine the maximum waterborne *A. salmonicida* concentrations arising from all possible overlaps between dispersal plumes coming from more than one farm.

Dispersal was simulated for two months (May and June 2010) and the maximum waterborne concentration was estimated by counting the number of active particles over specific volumes. Figure 6 shows the maximum concentrations (cfu/m³) over the complete duration of the simultaneous release of *A. salmonicida* from 18 farms rearing Atlantic Salmon vaccinated against furunculosis.

The highest estimated concentration of 1.5 x 10^6 cfu/m^3 arose after 18 days of continuous release and dispersion in May from the Cyrus Rock farm. For all times and volumes, the maximum concentration arose within a few kilometers of the primary contributing farm. Between 5 and 10 m depth, the maximum concentration arose from more than one farm where Brougham and Sonora Point contributed 56.2% and 43.8%, respectively, of the estimated concentration.

Table 13. Modelled concentrations of Aeromonas salmonicida *(cfu/m³) attributable to Atlantic Salmon farms in the Discovery Islands area. The model assumes all 18 Atlantic Salmon farms operating in the Discovery Islands area are simultaneously releasing bacteria over the months of May and June, and assuming an average of 514,000 fish on farm and an* A. salmonicida *exponential decay constant of 0.66 per day. All concentrations are modelled maxima computed over various depth ranges. Hour denotes the time that the maximum concentration occurred. Approximate location is the geographical location where the bacterial particles were observed to produce this maximum concentration.*

Depth range	Maximum [*A. salmonicida*] (cfu/m³)	Approximate location	Hour (GMT)	Contributing farm(s) and % contribution
0 – 5 m	1.5 x 10^6	5 km to the south of Cyrus Rocks	May 18, 14:00	Cyrus Rocks (100%)
5 – 10 m	6.0 x 10^5	2 km to the north of Brougham	June 10 18:00	Brougham (56.2%) Sonora Point (43.8%)
10 – 15 m	5.2 x 10^5	2.5 km to the southeast of Barnes Bay	May 8, 06:00	Barnes Bay (100%)
15 – 20 m	5.0 x 10^5	300 m to the south of Bickley	May 22, 16:00	Bickley (100%)
20 – 30 m	2.7 x 10^5	300 m to the south of Bickley	May 28, 19:00	Bickley (100%)
30 – 40 m	2.2 x 10^5	300 m to the south of Bickley	May 12, 22:00	Bickley (100%)
40 – 50 m	1.6 x 10^5	800 m to the west of Okisollo	May 31, 10:00	Okisollo (100%)

Concentrations reported in Table 13 take into account currents arising from tides, winds, freshwater discharge, heat flux, and bacterial decay in the water. The model assumes that all 18 Atlantic Salmon farms are simultaneously infected and releasing *A. salmonicida*, which though an extremely unrealistic scenario that has never been observed, is considered a worst-case scenario. Figure 6 shows the distribution of the modelled particles at 14:00 GMT on May 18, the time of maximum concentration in upper five meters of the water column.

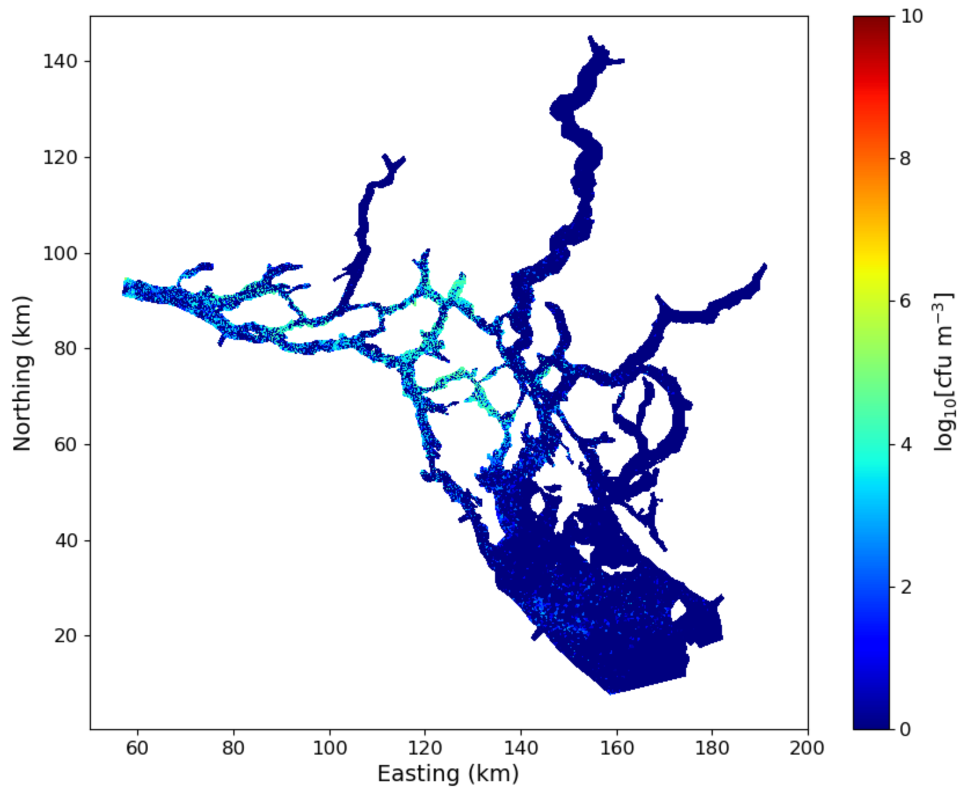

Figure 6. The modelled distribution of Aeromonas salmonicida *concentration in the upper five meters over 60 days of continuous shedding in the months May and June in the Discovery Islands area. The figure illustrates modelled distribution on May 18 at 14:00 GMT which corresponds to the time of maximum concentration.*

Hydrodynamic transmission of *A. salmonicida* in seawater has been reported between cages on an Atlantic Salmon farm in Ireland (Smith et al., 1982) and demonstrated using a simple particle tracking model in a Scottish loch (Rose, 1990). Based on this model, *A. salmonicida* was predicted to travel in the hypothetical loch for at least six to nine kilometers downstream from the fish farm (Rose, 1990) and hence supporting hydrodynamic dispersal and transmission of *A. salmonicida* in the marine environment.

3.4.3 Assumptions

- Fraser River Sockeye Salmon entering the Discovery Islands area naïve to *A. salmonicida*; and
- Fraser River Sockeye Salmon and other susceptible Pacific salmon species have been exposed to *A. salmonicida* released from Atlantic Salmon farm(s) operating in the Discovery Islands area.

3.4.4 Likelihood of infection

Table 14 presents the main factors contributing to and limiting the likelihood that a susceptible salmonid species would become infected with *A. salmonicida* released from an Atlantic Salmon farm located in the Discovery Islands area. These factors were used to determine the likelihood and uncertainty rankings based on definitions in Table 2, Table 5 and Table 6.

Table 14. Factors contributing to and limiting the likelihood that Fraser River Sockeye Salmon and other susceptible Pacific salmon species would become infected with Aeromonas salmonicida *released from Atlantic salmon farms in the Discovery Islands area under current fish health management practices.*

Contributing factors	Limiting factors
• Chinook, Coho, Pink, Chum and Sockeye salmon are susceptible to *A. salmonicida* infection and furunculosis; • Water temperature and salinity in the vicinity of Atlantic Salmon farms are suitable for *A. salmonicida* survival; • Transmission of *A. salmonicida* in the marine environment has been described (Smith et al., 1982); • Juvenile Sockeye Salmon could encounter Atlantic Salmon farms over three to eight days during their migration through the Discovery Islands area; and • Adult Sockeye Salmon could encounter Atlantic Salmon farms over two days during their migration through the Discovery Islands area.	• The estimated maximum waterborne concentration of *A. salmonicida* on an infected Atlantic Salmon farm (1.1 x 10^7 cfu/m^3 on an average size farm) is approximately one-ninth of the concentration that caused mortality after daily 12-h exposure for 21 days (1 x 10^8 cfu/m^3); • Based on telemetry study, juvenile Sockeye Salmon spend limited time (minutes) in the vicinity of fallowed farms (Rechisky et al., 2018); and • All farmed Atlantic Salmon reared in the Discovery Islands area are vaccinated against furunculosis.

The likelihood of infection was considered separately for the three exposure groups and resulted in the same conclusion.

It was concluded that the likelihood of at least one Fraser River Sockeye Salmon or other susceptible Pacific salmon species to become infected with *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area through waterborne exposure under the current fish health management practices is **very unlikely** given that the estimated waterborne concentration of *A. salmonicida* on an average Atlantic Salmon farm during an outbreak is approximately one-ninth of the concentration that did not cause infection in Atlantic Salmon after daily 12-h exposure for seven days (and required 12-h daily exposure for 21 days to cause mortality). Additionally, the likelihood of juvenile salmon swimming through the net pens and contacting infected fish is acknowledged but cannot be quantified. This conclusion was made with **reasonable uncertainty** given incomplete data and reliance on surrogate data.

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. Uncertainties were not combined.

Table 15 summarizes the likelihood assessment. It was concluded that the likelihood that wild susceptible fish would become infected with *A. salmonicida* released from Atlantic Salmon farms in the Discovery Islands area is **very unlikely** for all exposure groups.

Table 15. Summary of the likelihood and uncertainty rankings for the likelihood assessment of the Aeromonas salmonicida *risk assessment. Results are reported in white cells and likelihood combination results are reported in shadowed cells under the "Rankings" column.*

<table>
<tr><th colspan="2">Steps</th><th colspan="6">Rankings</th></tr>
<tr><td>Farm infection assessment</td><td>Likelihood of farm infection</td><td colspan="6">Unlikely
(reasonable certainty)</td></tr>
<tr><td rowspan="3">Release assessment</td><td>Release pathways</td><td colspan="3">Farmed Atlantic Salmon</td><td colspan="3">Mechanical vectors and fomites</td></tr>
<tr><td>Likelihood of release</td><td colspan="3">Extremely likely
(high certainty)</td><td colspan="3">Unlikely
(reasonable certainty)</td></tr>
<tr><td>Combined likelihoods of release</td><td colspan="6">Extremely likely</td></tr>
<tr><td rowspan="3">Exposure and infection assessment s</td><td>Exposure groups</td><td colspan="2">Juvenile Fraser River Sockeye Salmon</td><td colspan="2">Adult Fraser River Sockeye Salmon</td><td colspan="2">Other susceptible Pacific salmon species</td></tr>
<tr><td>Likelihood of exposure</td><td colspan="2">Likely
(reasonable certainty)</td><td colspan="2">Likely
(reasonable certainty)</td><td colspan="2">Extremely likely
(reasonable uncertainty)</td></tr>
<tr><td>Likelihood of infection</td><td colspan="2">Very unlikely
(reasonable uncertainty)</td><td colspan="2">Very unlikely
(reasonable uncertainty)</td><td colspan="2">Very unlikely
(reasonable uncertainty)</td></tr>
<tr><td colspan="2">Combined exposure and infection likelihoods for each exposure group</td><td colspan="2">Very unlikely</td><td colspan="2">Very unlikely</td><td colspan="2">Very unlikely</td></tr>
<tr><td colspan="2">Combined likelihoods (farm infection, release, exposure and infection) for each exposure group</td><td colspan="2">Very unlikely</td><td colspan="2">Very unlikely</td><td colspan="2">Very unlikely</td></tr>
</table>

4 CONSEQUENCE ASSESSMENT

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

Based on the farm infection assessment, it was determined that it is unlikely that Atlantic Salmon infected with *A. salmonicida* would be present on at least one farm in the Discovery Islands area. In years with no *A. salmonicida* infections on farms, no consequence to the abundance and diversity of Fraser River Sockeye Salmon would be attributable to the bacterium on Atlantic Salmon farms in the Discovery Islands area. In years with evidence of *A. salmonicida* infection on farms, the exposure assessment determined that infected fish have been present on a maximum of one farm in any given month (see Table 11). The overall likelihood assessment concluded that it is very unlikely for Fraser River Sockeye Salmon to become infected with *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area under current management practices.

Notwithstanding this conclusion and assuming that at least one susceptible wild fish would have been infected with *A. salmonicida* attributable to those farms, the consequence assessment explores the potential magnitude of impacts on the number of returning adults and diversity of Fraser River Sockeye Salmon.

4.1 QUESTION

Assuming that at least one susceptible wild fish has been infected with *A. salmonicida* 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 infection dynamics; sublethal impacts of infection; estimates of Fraser River Sockeye Salmon densities; proportion of Fraser River Sockeye Salmon potentially exposed to infected farms; and exposure over two generations.

4.2.1 *Aeromonas salmonicida* infection dynamics

Disease outbreaks occur when conditions are unfavourable to the host (environmental and physiological stress) and favourable to the pathogen (immunocompromised host, pathogen survival in the environment). A minimum number of infected and diseased fish with sufficient contact with susceptible hosts is required for an infection to establish and spread into a population.

Horizontal transmission is the main mode of transmission (Roberts, 2012). The time period between exposure and first mortality observed in immersion studies ranges between one to two days in Chinook Salmon (< 20 g fish exposed for 15 min in freshwater at 4.8×10^3 cells of *A. salmonicida*/mL) (Beacham and Evelyn, 1992) and 24 days in Atlantic Salmon (75 to 115 g fish exposed daily for 12 h for 21 days in seawater at 10^2 CFU of *A. salmonicida*/mL) (Rose et al., 1989).

Host population density is an important factor in the dynamics of furunculosis epizootics with disease specific mortalities decreasing with reductions in host densities under laboratory conditions in freshwater with Chinook Salmon (1.7 g) (Ogut and Reno, 2004; Ogut et al., 2005). More specifically:

- infection and furunculosis specific mortalities were observed at densities ranging between 9.13 to 0.36 fish/L (equivalent to 9,130 to 360 fish/m^3);
- transmission of infection without epizootics in the population was observed within the duration of the experiment (23 to 33 days) at densities ranging between 0.19 to 0.06 fish/L (equivalent to 190 to 60 fish/m^3);
- no transmission of infection was observed over a 33 day period at 0.03 fish/L (equivalent to 30 fish/m^3).

Although the above density values are specific to the experimental conditions, they support the idea that a critical density of the host population is required for the effective transmission of *A. salmonicida* and progression of disease.

4.2.2 Sublethal impacts of *Aeromonas salmonicida* infection

It is recognized that there can be both sublethal and cumulative effects of exposure to pathogens. Documented sublethal effects due to furunculosis are scarce and there are none documented in wild fish populations. No publications were found on the effects of chronic furunculosis infections (Boily et al., 2019).

Laboratory studies have been conducted on other salmonid species that suggest that there can be physiological effects resulting from infection (Ellis et al., 2007; Yi et al., 2016); however, it is unknown whether sublethal exposure to *A. salmonicida* would result in increased or decreased resistance to further infection with *A. salmonicida* and/or other pathogens. There are no data available to suggest what the physiological or resulting population level effects of infection would be on Fraser River Sockeye Salmon.

4.2.3 Estimates of Fraser River Sockeye Salmon densities

Following infection with a pathogen, the spread of infection within a population depends, amongst other parameters, on the density of the population. As this risk assessment considers the potential spread of infection acquired from Atlantic Salmon farm(s) in the Discovery Islands area, in-river juvenile density estimates are not relevant. Of most relevance to this assessment are the densities in the Discovery Islands area and in the open ocean.

4.2.3.1 During juvenile outmigration

Approximate densities of juvenile Sockeye Salmon in the Strait of Georgia were estimated from purse seine data collected in May and June of 2010-2012 (Neville et al., 2013; Freshwater et al., 2017). These studies used a 280 m long and 9 m deep purse seine (approximate cylindrical volume of 56,000 m^3). The highest reported average CPUE for Fraser River Sockeye Salmon was 1,534 and occurred in the Discovery Islands area in June of 2012 (Neville et al., 2013). Average CPUEs in the Strait of Georgia in May and June were at least an order of magnitude lower (Neville et al., 2013)). Using the same dataset, (Freshwater et al., 2017) reported May and June combined CPUEs of 49 ± 239 and 323 ± 780 (average ± SD) for 2011 and 2012, respectively.

Based on the highest average CPUE (1,534) and assuming that the water sampled in each set was 56,000 m^3, the highest estimated average density of juvenile Sockeye Salmon in this area would be approximately 0.03 fish/m^3. Note that these estimates assume that fish are uniformly distributed within the area sampled by the net, and that all fish present in the sampled area are caught (i.e., there is no net avoidance behaviour or fish escaping from the net). These estimates should be revised as results from on-going studies become available.

4.2.3.2 In the open ocean

There are no data on Sockeye Salmon abundance or density in the open ocean, hence proxy data were used in this risk assessment.

Using hydro acoustic methods, Nero and Huster (1996) estimated the mean density of salmon (spp.) to 114 salmon/km^2 in the Gulf of Alaska (which they mention is comparable with historical estimates of 160 salmon/km^2). As salmon were at most 40 m from the sea surface during the day (Nero and Huster, 1996), their average density is therefore estimated to be approximately 2.9×10^{-6} fish/m^3. Assuming that salmon mainly stay in the top 10 meters, this is where the greatest concentration would occur (Ware and McFarlane (1989); Groot and Margolis (1991); cited in Nero and Huster (1996)), their density would be approximately 1.1×10^{-5} fish/m^3. Note that Nero and Huster (1996) did not specify salmon species or sizes.

As the spatial arrangement of salmon suggests that at small spatial scales (2–200 m), salmon are uniformly distributed, whereas at larger spatial scales (400–2000 m), they are aggregated (Nero and Huster, 1996), the density at small scales could be higher than the average estimates above. However, although data are limited, it is reasonable to anticipate that the density of Fraser River Sockeye Salmon would be lower at sea than during their migration through the channels of the Discovery Islands area.

4.2.4 Estimates of the proportion potentially exposed to infected farms

This section explores the proportion of Fraser River Sockeye Salmon population in the Discovery Islands area at the same time as *A. salmonicida* infections and/or furunculosis have been reported on Atlantic Salmon farms.

Noting that there are routes through the Discovery Islands area where there are no Atlantic Salmon farms, and that location and number of simultaneously infected farms will be critical aspects in assessing actual exposure to infected farm(s), the following analysis provides an overestimate of the proportion of the population exposed to infected farms in the Discovery Islands area during periods when *A. salmonicida* infections and/or furunculosis were detected on one or more farms.

This is the first step in determining the proportion of the population that could potentially be exposed to *A. salmonicida* attributable to infected Atlantic Salmon farms in the Discovery Islands area acknowledging that concurrent overlap does not necessarily result in exposure and that exposure does not necessarily result in infection. The estimates are based on the timing of Fraser River Sockeye Salmon migration and evidence of infections on farms in the area.

4.2.4.1 Juvenile

Millions of juvenile Fraser River Sockeye Salmon migrate through the Discovery Islands area every year (reviewed in Grant et al. (2018)). 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 an infected Atlantic Salmon farm based on their migration routes. It was therefore assumed that all out-migrating juvenile Fraser River Sockeye Salmon could potentially be exposed to *A. salmonicida* 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.

However, as Atlantic Salmon farms are not located in every channel and do not occupy a large volume of the Discovery Islands area (see Figure 1 and section 3.3.2.2), it is reasonable to assume that not all fish would encounter an infected farm or be exposed to pathogens dispersed from the farm(s). Additionally, these estimates need to consider the presence of Fraser River Sockeye Salmon in the area in relation to the timing of the infections. Juvenile lake-type Fraser River Sockeye Salmon migrate through the Discovery Islands area from mid-May to mid-July (Grant et al., 2018). The outmigration is, however, not uniformly distributed over the three months (Neville et al., 2016; Freshwater et al., 2019). Based on capture data from Freshwater et al. (2019), 30%, 62% and 8% of juveniles were captured in May, June and July, respectively.

Taking into consideration the temporal distribution of Fraser River Sockeye Salmon through the Discovery Islands area and only considering years with infection, between 30 and 62% (median=62% and mean=51%) of juveniles would have had the opportunity to be exposed to *A. salmonicida* attributable to Atlantic Salmon farm(s) in the Discovery Islands area during their out-migration migration (Appendix E). These estimates also assume that migrating fish would encounter the infected farm(s), i.e., fish would use the route(s) which have the infected farm(s).

4.2.4.2 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 2017 (Pacific Salmon Commission, 2017; Grant et al., 2018; Pacific Salmon Commission, 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.

Returning adult Fraser River Sockeye Salmon migrate through the Discovery Islands area from late-June to early-October (reviewed in Grant et al. (2018)). The returning migration is, however, not uniformly distributed over the five months. Based on capture data below Mission, provided by the Pacific Salmon Commission (see Appendix E), 0.3%, 12.2%, 79.7%, 7.7% and 0.1% of returning adults are expected in the Discovery Islands area in the months of June, July, August, September and October, respectively.

Taking into consideration the temporal distribution and the northern diversion of returning adults (see Appendix E) and only considering years with infections, between 0.2% and 62.1% (median=0.3% and mean=20.9%) of adults would have had the opportunity to be exposed to *A. salmonicida* attributable to Atlantic Salmon farm(s) in the Discovery Islands area during their returning migration (Appendix E). These estimates also assume that migrating fish would encounter the infected farm(s), i.e., fish would use the route(s) which have the infected farm(s).

4.2.5 Estimates of exposure over two generations

The potential exposure of Fraser River Sockeye Salmon populations to Atlantic Salmon farms infected with *A. salmonicida* over two generations (eight years for Fraser River Sockeye Salmon) was estimated to explore potential impacts on diversity.

Given the two possible exposure outcomes in any given year for migrating Fraser River Sockeye Salmon, i.e., migrating salmon can be exposed given evidence of infection on farms in the area (success outcome) or migrating salmon cannot be exposed given lack of evidence of infection on farms in the area (failure outcome), the number of successes (s) over a given number of trials (n) can be estimated using the binomial process (Appendix F).

On average, over two generations, Fraser River Sockeye Salmon (juveniles and adults) could encounter Atlantic Salmon farms in the Discovery Islands area infected with *A. salmonicida* in two of the eight years. This assumes that when a farm(s) is infected, the Sockeye Salmon choose the route(s) that takes them by the infected farm(s). The probability of exposure, but not necessarily infection, to occur in at least four consecutive years over two generations (eight years) is 0.33% for both juvenile and adult Fraser River Sockeye Salmon (see Appendix F).

Despite the potential exposure over two generations, the likelihood assessment concluded that it was very unlikely for Fraser River Sockeye Salmon to become infected with *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area under current management practices.

4.3 ASSUMPTIONS

- There is no correlation between furunculosis mortality and marine mortality from other sources in Sockeye Salmon; i.e., the marine mortality rate is the same in infected and non-infected fish; and
- When a farm(s) is infected, the Sockeye Salmon use the route(s) that takes them by the infected farm(s).

4.4 MAGNITUDE OF CONSEQUENCES

Figure 7 illustrates potential outcomes of spread and establishment resulting from at least one Fraser River Sockeye Salmon infected with *A. salmonicida* released from infected Atlantic Salmon on farms located in the Discovery Islands area.

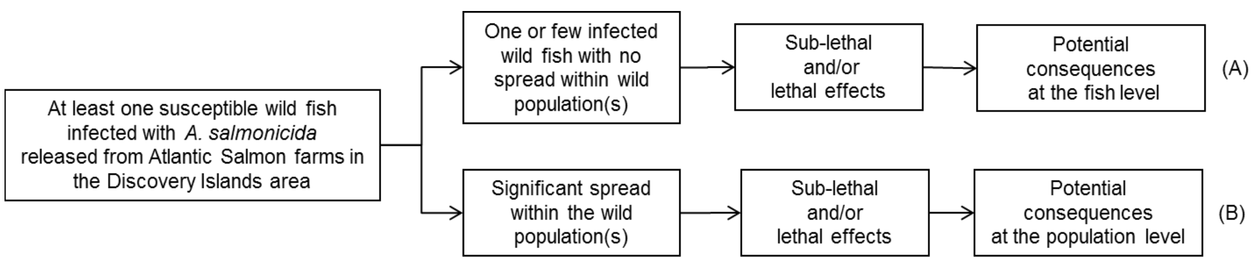

Figure 7. Potential outcomes resulting from at least one susceptible wild fish infected with Aeromonas salmonicida *released from Atlantic Salmon farms located in the Discovery Islands area.*

Based on the information above it is concluded that no or at most, very few Fraser River Sockeye Salmon will be infected, which will lead to negligible consequences at the population level. Should one or a few fish become infected, with no spread within the population, sublethal and or lethal effects may result in consequences to the fish level (Outcome A).

The potential magnitude of consequence on both the abundance and diversity of Fraser River Sockeye Salmon resulting from the exposure to an Atlantic Salmon farm infected with *A. salmonicida* was assessed separately for juvenile Fraser River Sockeye Salmon, adult Fraser River Sockeye Salmon and other susceptible species. Rankings were determined referring to consequence to abundance (Table 3), consequences to diversity (Table 4) and uncertainty (Table 5) definitions.

4.4.1 Juvenile Fraser River Sockeye Salmon

Juvenile Fraser River Sockeye Salmon are expected to encounter *A. salmonicida*-infected Atlantic Salmon farms in the Discovery Islands area during their out-migration in one of eight years; and have almost a zero probability of exposure to occur over four consecutive years (section 4.2.5). In years with infections, based on 2002-2017 data (Table 11), juveniles could have been exposed to one *A. salmonicida*-infected farm during their migration through the Discovery Islands area.

Following exposure to one farm with infected Atlantic Salmon in the Discovery Islands area, juvenile Fraser River Sockeye Salmon will continue their migration through Johnstone Strait, Queen Charlotte Strait, and into the open ocean. The potential for an infection acquired in the Discovery Islands area to spread to other juvenile Fraser River Sockeye Salmon during migration at sea is considered (Figure 7, Outcome A).

The estimated migration period from the Discovery Islands area through Queen Charlotte Strait is approximately five to 15 days based on juvenile migration swimming speed (10 to 30 km/day) summarized in Grant et al. (2018). Based on laboratory studies, the time between exposure to waterborne *A. salmonicida* and mortality can be up to 24 days in Atlantic Salmon in saltwater (Rose et al., 1989). Additionally, latent *A. salmonicida* infections can develop into disease following stress events, so it is probable that an exposed juvenile Fraser River Sockeye Salmon would only show signs of *A. salmonicida* infection attributed to a farm following migration through Johnstone and Queen Charlotte Straits or in the open ocean.

Whether or not infection will spread in the population, as well as the rate and extent of the spread, depends on the probability of susceptible individuals making successful contact (i.e., contact leading to transmission of the infection) with an infectious individual in the same population. This probability depends, amongst other parameters, on the density of the population (Reno, 1998). Data on population density during furunculosis epizootics is limited to: (1) laboratory studies in freshwater with Chinook Salmon (1.7 g) (Ogut and Reno, 2004; Ogut et al., 2005); and (2) FHEs attributed to furunculosis in Atlantic Salmon farms in the Discovery Islands area.

The density at which no detectable transmission of *A. salmonicida* was observed between Chinook Salmon fry in freshwater under experimental conditions (30 fish/m^3) is three orders of magnitude higher than the highest estimated average density of juvenile Fraser River Sockeye Salmon (0.03 fish/m^3) in the Discovery Islands area. For comparison, the average density of vaccinated Atlantic Salmon (91 ± 19 g) during a FHE attributed to typical furunculosis in the Discovery Islands area is 3.02 ± 1.82 fish/m^3.

Although based on surrogate information, this suggests that it is unlikely that the critical density of the host population required for the effective transmission of *A. salmonicida* and progression of the disease would be met for juvenile Fraser River Sockeye Salmon.

Consequently, it was concluded that it is not plausible for juvenile Fraser River Sockeye Salmon exposed to the estimated concentrations of *A. salmonicida* to be released from one farm with infected Atlantic Salmon to result in an infection that would spread and establish within the population. This is primarily based on the biology of *A. salmonicida*. Therefore, it is concluded that the potential magnitude of consequences to the population abundance or diversity of Fraser River Sockeye Salmon would be **negligible**. This conclusion was made with **reasonable uncertainty** given high reliance on surrogate data.

4.4.2 Adult Fraser River Sockeye Salmon

Adult Fraser River Sockeye Salmon could be exposed to one farm with infected Atlantic Salmon during their return migration through the Discovery Islands to the Fraser River; and have almost a zero probability of exposure to occur over four consecutive years (section 4.2.5). The potential for an infection acquired in the Discovery Islands area to spread to other adult Fraser River Sockeye Salmon during freshwater migration or on the spawning grounds (prior to successful spawning) is considered.

Grant et al. (2018) estimated that 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. 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). In a fish health study, the Early Stuart River Sockeye took up to about a month to reach spawning grounds (Stoddard, 1993). Given that in laboratory studies the time between exposure and mortality in small salmonids can be up to 24 days in laboratory studies (reported by Rose et al. (1989) in 75 to 115 g Atlantic Salmon in saltwater) and the time for Early Stuart Sockeye Salmon (used as a reference point for migration time (i.e., up to 30 days)), some adult Sockeye Salmon could reach the spawning grounds with clinical signs of disease.

Since the critical density of adult Sockeye Salmon required for the effective transmission of *A. salmonicida* to susceptible fish and progression of the disease in the marine environment and on spawning grounds is not available, a stochastic, frequency-dependent compartmental susceptible-exposed-infected-recovered (SEIR) model with disease-induced mortality (Keeling and Rohani, 2007) was built to explore the conditions under which the pathogen could spread in the population. Because the parameters in the model are unknown for wild Sockeye Salmon, different combinations of model parameters (based on surrogate data and assumptions) were compared (see Appendix G for details).

The parameters for the SEIR model were based on laboratory experiments conducted with Chinook Salmon fry exposed to *A. salmonicida* by co-habitation in freshwater (Ogut et al., 2004; Ogut et al., 2005; Ogut and Reno, 2005). Under conditions including a basic reproductive ratio (R_0) of 3.25 (based on 1.97 g Chinook Salmon in Ogut et al. (2004)), disease-induced mortality would start increasing slowly around 70 days post exposure to reach 1% of the population around day 120; in 32% of the iterations, no significant spread occurred. This suggests that significant spread of infection acquired in the Discovery Islands area is not a plausible outcome for adult Fraser River Sockeye Salmon, as they are expected to die of natural causes before any other outcome.

Recognizing that the initial parameters may not be reflective of the environment or the fish species, the SEIR model was rerun to examine the conditions under which a significant proportion of the adult Fraser River Sockeye Salmon population would become infected and die from furunculosis. Modelling results suggest that a $R_0 \geq 12$ would be required to obtain a mortality rate of 1% within 35 days post exposure under the same conditions. Even by changing other parameters to sometimes unrealistic values, it was not possible to reach 1% cumulative mortality within 35 days with values of $R_0 \leq 7$ (see Appendix G for details). Diseases with R_0 of five or higher are considered very contagious and in well-mixed populations almost all individuals are likely to contract the disease. It is extremely unlikely that the basic reproductive ratio of *A. salmonicida* would be this high in wild salmon. Still using the same parameters as above, the number of initially infected fish that would be required in order to see a significant proportion of the population dying within 35 days post exposure was also explored. At $R_0 = 3.25$, one thousand initially infected fish would be required; at $R_0 = 5$, four hundred initially infected fish; and at $R_0 = 8$, approximately 50 initially infected fish would be required. However, given the conclusions of the infection assessment, and given the discussion on the basic reproductive ratio above, these conditions are extremely unlikely to be present in adult Sockeye Salmon.

Based on this modelling exercise, it is expected that there would not be significant spread of infection within the returning adult Sockeye Salmon population prior to spawning. Therefore, it is concluded that the potential magnitude of consequences to the population abundance or diversity of Fraser River Sockeye Salmon would be **negligible**. This conclusion was made with **reasonable uncertainty** given the reliance on surrogate data and modelling.

4.4.3 Other susceptible Pacific salmon species

It was concluded that the potential magnitude of indirect consequences to both the abundance and diversity of Fraser River Sockeye Salmon resulting from an infection with *A. salmonicida* in other susceptible species attributable to Atlantic Salmon farms in the Discovery Islands area under the current fish health management practices would be **negligible** as the direct magnitude of consequences on Fraser River Sockeye Salmon were determined to be negligible and there is no evidence to suggest that indirect consequences would be of higher magnitude than direct ones. This conclusion was made with **reasonable uncertainty** given the lack of data on the impact that *A. salmonicida*-related changes in other susceptible Pacific salmon species populations might have on Fraser River Sockeye Salmon abundance and diversity.

5 RISK ESTIMATION

5.1 ABUNDANCE

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

Table 16. Risk estimates to the abundance of Fraser River Sockeye Salmon resulting from Aeromonas salmonicida *attributable to Atlantic Salmon farms located in the Discovery Islands area under current farm management practices.*

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

The risk to Fraser River Sockeye Salmon abundance resulting from potential ecological consequences due to infections of other susceptible Pacific salmon species with *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area was also considered and found to be minimal.

It was concluded that, under the current fish health management practices, the risk to the abundance of Fraser River Sockeye Salmon as a result of an *A. salmonicida* infection attributable to Atlantic Salmon farms operating in the Discovery Islands area is **minimal**.

5.2 DIVERSITY

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

Table 17. Risk estimates to the diversity of Fraser River Sockeye Salmon resulting from Aeromonas salmonicida *attributable to Atlantic Salmon farms located in the Discovery Islands area under current farm management practices.*

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

The risk to Fraser River Sockeye Salmon diversity resulting from potential ecological consequences due to infections of other susceptible Pacific salmon species with *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area was also considered and found to be minimal.

It was concluded that, under the current fish health management practices, the risk to the diversity of Fraser River Sockeye Salmon as a result of an *A. salmonicida* infection attributable to Atlantic Salmon farms operating in the Discovery Islands area is **minimal**.

6 SOURCES OF UNCERTAINTIES

There are uncertainties associated with both the likelihood and consequence assessments. 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).

6.1 LIKELIHOOD ASSESSMENT

The main uncertainties related to the likelihood assessment are attributed to:

- the lack of data to estimate population prevalence of *A. salmonicida* in farmed Atlantic Salmon in marine net pens;
- reliance on a single laboratory study to estimate the shedding rates from *A. salmonicida* infected Atlantic Salmon;
- the minimal infectious and lethal doses of *A. salmonicida* in Sockeye Salmon are unknown;
- the variability and knowledge gaps about precise migration routes of juvenile Fraser River Sockeye Salmon through the Discovery islands area; and
- the lack of data to precisely estimate the proportion of the population that would be exposed and infected with *A. salmonicida* released from an Atlantic Salmon farm in the Discovery Islands area.

6.2 CONSEQUENCE ASSESSMENT

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

- the lack of a model of disease spread within migrating fish populations;
- the lack of data on furunculosis mortality in wild Sockeye Salmon and other susceptible species; and

- the lack of knowledge of the consequences at the population level resulting from sublethal infections with *A. salmonicida*.

7 CONCLUSIONS

The assessment concluded that *A. salmonicida* attributable to Atlantic Salmon farms operating in the Discovery Islands area poses minimal risk to Fraser River Sockeye Salmon abundance and diversity under the current fish health management practices.

Two main factors influenced the attribution of the minimal risk. First, it was determined that it is very unlikely that susceptible fish would become infected with *A. salmonicida* released from an Atlantic Salmon farm in the Discovery Islands area. Second, even in the very unlikely event that wild susceptible fish would become infected with *A. salmonicida* due to Atlantic Salmon farms in the Discovery Islands, the infection would not be expected to spread within wild populations, hence the magnitude of consequences to both Fraser River Sockeye Salmon abundance and diversity would be negligible.

There are considerable sources of uncertainties associated to the determination of the risk to Fraser River Sockeye Salmon due to *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area. The main uncertainties are related to the assessments of the (1) likelihood of infection of wild fish for which there is a lack of information about shedding rates in *A. salmonicida* carriers; interaction of wild populations with Atlantic Salmon farms, and minimum infectious and lethal dose of *A. salmonicida* in Sockeye Salmon and other susceptible species; and (2) consequence assessment for which there are no data on furunculosis mortality in wild susceptible wild fish, spread of infection within migrating populations of fish and consequences at the population level resulting from sublethal infections. Conclusions of this risk assessment should be reviewed as new research findings fill knowledge gaps or if conditions were to change.

8 REFERENCES CITED

Allen, L. J. S., Jang, S. R. and Roeger, L.-I. 2017. Predicting population extinction or disease outbreaks with stochastic models. Letters in Biomathematics 4(1): 1-22.

Beacham, T. D., Beamish, R. J., Candy, J. R., Wallace, C., Tucker, S., Moss, J. H. and Trudel, M. 2014. Stock-specific migration pathways of juvenile sockeye salmon in British Columbia waters and in the Gulf of Alaska. Trans. Am. Fish. Soc. 143(6): 1386-1403.

Beacham, T. D. and Evelyn, T. P. T. 1992. Genetic variation in disease resistance and growth of Chinook, coho, and chum salmon with respect to vibriosis, furunculosis, and bacterial kidney disease. Trans. Am. Fish. Soc. 121(4): 456-485.

Bernoth, E.-M. 1997. Chapter 1 - Furunculosis: the history of the disease and of disease research. *In* Furunculosis. Academic Press, San Diego. pp 1-20.

Boily, F., Malcolm, G. and Johnson, S. 2019. Characterization of *Aeromonas salmonicida* and furunculosis to inform pathogen transfer risk assessments in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/016. vi + 39 p.

Bravender, B. A., Anderson, S. S. and Van Tine, J. 1999. Distribution and abundance of juvenile salmon in Discovery Harbour Marina and surrounding area, Campbell River, B.C., during 1996. Can. Tech. Rep. Fish. Aquat. Sci. 2292. 45 p.

Brown, T. J., Kask, B. A., McAllister, C. D., Macdonald, J. S. and Levings, C. D. 1984. Salmonid catch-data from Campbell River and Discovery Passage, 1984. Can. Data Rep. Fish. Aquat. Sci. 497. iii + 79 p.

Brown, T. J., McAllister, C. D. and Kotyk, M. 1987. A summary of the salmonid catch - Data from Campbell River Estuary and Discovery Passage for the years 1982 to 1986. Can. Data Rep. Fish. Aquat. Sci. 650. 99 p.

CFIA. 2018a. Federally Reportable Aquatic Animal Diseases in Canada - 2018.

CFIA. 2018b. Veterinary biologics licensed in Canada.

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.

Cipriano, R. C. and Heartwell, C. M. 1986. Susceptibility of salmonids to furunculosis: differences between serum and mucus responses against *Aeromonas salmonicida*. Trans. Am. Fish. Soc. 115(1): 83-88.

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. vi + 57 p.

DFO. 2015. Marine finfish aquaculture licence under the Fisheries Act. Aquaculture Management Division. Fisheries and Oceans Canada. 59 p.

DFO. 2018a. Fish health events at British Columbia marine finfish aquaculture sites. Fisheries and Oceans Canada.

DFO. 2018b. Mortality events at British Columbia marine finfish aquaculture sites. Fisheries and Oceans Canada.

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

Effendi, I. and Austin, B. 1991. Survival of the fish pathogen *Aeromonas salmonicida* in seawater. FEMS Microbiol. Lett. 84(1): 103-106.

Effendi, I. and Austin, B. 1994. Survival of the fish pathogen *Aeromonas salmonicida* in the marine environment. J. Fish Dis. 17(4): 375-385.

Ellis, T., Bagwell, N., Pond, M., Baynes, S. and Scott, A. P. 2007. Acute viral and bacterial infections elevate water cortisol concentrations in fish tanks. Aquaculture 272(1-4): 707-716.

Enger, Ø., Gunnlaugsdottir, B., Thorsen, B. K. and Hjeltnes, B. 1992. Infectious load of *Aeromonas salmonicida* subsp. *salmonicida* during the initial phase of a cohabitant infection experiment with Atlantic salmon, *Salmo salar* L. J. Fish Dis. 15(5): 425-430.

Enger, Ø. and Thorsen, B. K. 1992. Possible ecological implication of the high cell surface hydrophobicity of the fish pathogen *Aeromonas salmonicida*. Can. J. Microbiol. 38: 1048-1052.

Evelyn, T. P. T. 1971. Aberrant strain of bacterial fish pathogen *Aeromonas salmonicida* isolated from a marine host, sablefish (*Anoplopoma fimbria*), and from 2 species of cultured Pacific salmon. J. Fish. Res. Board Can. 28(10): 1629-1634.

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

Ferguson, N. M., Donnelly, C. A. and Anderson, R. M. 2001. The foot-and-mouth epidemic in Great Britain: pattern of spread and impact of interventions. Science 292(5519): 1155-1160.

Foreman, M. G. G., Chandler, P. C., Stucchi, D. J., Garver, K. A., Guo, M., Morrison, J. and Tuele, D. 2015. 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.

Fraser, D. I., Munro, P. D. and Smail, D. A. 2006. Disinfection guide version IV: practical steps to prevent the introduction and minimise transmission of diseases of fish. *In* Fisheries Research Services Internal Report No 13/06. Aberdeen, Scotland, UK. 25 p.

Freshwater, C., Trudel, M., Beacham, T. D., Gauthier, S., Johnson, S. C., Neville, C. E. and Juanes, F. 2019. Individual variation, population-specific behaviours and stochastic processes shape marine migration phenologies. J. Anim. Ecol. 88(1): 67-78.

Freshwater, C., Trudel, M., Beacham, T. D., Grant, S. C. H., Johnson, S. C., Neville, C. E. M., Tucker, S. and Juanes, F. 2017. Effects of density during freshwater and early marine rearing on juvenile sockeye salmon size, growth, and migration. Mar. Ecol. Prog. Ser. 579: 97-110.

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.

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

Gillespie, D. T. and Petzold, L. R. 2003. Improved leap-size selection for accelerated stochastic simulation. J. Chem. Phys. 119(16): 8229-8234.

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.

Groot, C. and Cooke, K. 1987. Are the migrations of juvenile and adult Fraser River sockeye salmon (O*ncorhynchus nerka)* in near-shore waters related? Can. Spec. Publ. Fish. Aquat. Sci. 96: 53-60.

Groot, C. and Margolis, L. 1991. Pacific salmon life histories. University of British Columbia Press, Vancouver, B. C. 564 p.

Hiney, M. 1995. Detection of stress inducible furunculosis in salmonids vaccinated with water and oil-based furunculosis vaccines. Bull. Eur. Ass. Fish Pathol. 15(3): 98-99.

Hiney, M. and Olivier, G. 1999. Furunculosis (*Aeromonas salmonicida*). *In* Fish diseases and disorders. Woo, P. T. K. and Bruno, D. W. (eds.). Vol 3: pp 341-425.

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

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.

Johnson, B. 2016. Development and evaluation of a new method for assessing migration timing of juvenile Fraser River sockeye salmon in their early marine phase. Undergraduate Thesis. University of Northern British Columbia. 33 p.

Keeling, M. J. and Rohani, P. 2007. Modeling infectious diseases in humans and animals. Princeton University Press, Princeton, New Jersey. 408 p.

Kent, M. 2011. Infectious diseases and potential impacts on survival of Fraser River sockeye salmon. *In* Cohen Commission Technical Report. 1: 58 p.

Kent, M. L. 1992. Diseases of seawater netpen-reared salmonid fishes in the Pacific Northwest. Can. Spec. Publ. Fish. Aquat. Sci. Vol. 116. DFO. PBS, Nanaimo, BC. 1-76 p.

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.

Levings, C. D. and Kotyk, M. 1983. Results of two boat trawling for juvenile salmonids in Discovery Passage and nearby channels, Northern Strait of Georgia. Can. Man. Rep. Fish. Aquat. Sci. No. 1730. 55 p.

Lund, M. 1967. A study of the biology of *Aeromonas salmonicida*. Thesis (MSc Thesis) Depertment of Agriculture, University of Newcastle-upon-Tyne.

MacDiarmid, S. C. 1994. The risk of introducing exotic diseases of fish into New Zealand through the importation of ocean-caught Pacific salmon from Canada. Ministry of Agriculture and Fisheries New Zealand. 161 p.

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.

Manzer, J. I. 1955. Pink and chum salmon tagging experiments in Johnstone Straits and Discovery Passage, 1953. Biological Station, Fisheries Research Board of Canada, Nanaimo, BC. 35 p.

McCarthy, D. 1983. An experimental model for fish furunculosis caused by *Aeromonas salmonicida*. J. Fish Dis. 6(3): 231-237.

McCarthy, D. H. 1977. Some ecological aspects of the bacterial fish pathogen - *Aeromonas salmonicida. In* Aquatic microbiology. Academic Press. Vol. 6: pp 299-324.

Midtlyng, P. 1997. Vaccination against furunculosis. *In* Furunculosis: multidisciplinary fish disease research. Bernoth, E. M., Ellis, A. E., Midtlyng, P., Olivier, G. and Smith, P. (eds.). Academic Press, San Diego. pp 382-404.

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. 2020. 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. ix + 56 p.

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.

Munro, A. L. S. and Waddell, I. F. 1984. Furunculosis: experience of its control in the sea water cage culture of Atlantic salmon in Scotland. Int. Counc. Explor. Sea Coop. Res. Rep. F(32): 1-9.

Nero, R. W. and Huster, M. 1996. Low frequency acoustic imaging of Pacific salmon on the high seas. Can. J. Fish. Aquat. Sci. 53: 2513-2523.

Neville, C. M., Johnson, S. C., Beacham, T. D., Whitehouse, T., Tadey, J. and Trudel, M. 2016. Initial estimates from an integrated study examining the residence period and migration timing of juvenile sockeye salmon from the Fraser River through coastal waters of British Columbia. NPAFC Bull. 6: 45-60.

Neville, C. M., Trudel, M., Beamish, R. J. and Johnson, S. C. 2013. The early marine distribution of juvenile sockeye salmon produced from the extreme low return in 2009 and the extreme high return in 2010. North Pacific Anadromous Fish Commission 9: 65-68.

Ogut, H. 2001. Biological and mathematical modeling of dynamics of furunculosis in Chinook salmon (*Oncorhynchus tshawvtscha*) and infectious hematopoietic necrosis (IHN) in rainbow trout (*Oncorhynchus mykiss*). Thesis (Fisheries Sciences, PhD) Oregon State University. 193 p.

Ogut, H., LaPatra, S. E. and Reno, P. W. 2005. Effects of host density on furunculosis epidemics determined by the simple SIR model. Prev. Vet. Med. 71(1-2): 83-90.

Ogut, H. and Reno, P. 2004. Prevalence of furunculosis in Chinook salmon depends on density of the host exposed by cohabitation. N. Am. J. Aquacult. 66(3): 191-197.

Ogut, H. and Reno, P. W. 2005. Evaluation of an experimental *Aeromonas salmonicida* epidemic in Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). J. Fish Dis. 28: 263-269.

Ogut, H., Reno, P. W. and Sampson, D. 2004. A deterministic model for the dynamics of furunculosis in Chinook salmon *Oncorhynchus tshawytscha.* Dis. Aquat. Org. 62: 57-63.

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.

Pacific Salmon Commission. 2017. Report of the Fraser River Panel to the Pacific Salmon Commission on the 2016 Fraser River Sockeye Salmon fishing season. *In* Annual Reports of the Fraser River Panel to Pacific Salmon Commission. Vancouver, BC. 1-61 p.

Pacific Salmon Commission. 2018. Report of the Fraser River Panel to the Pacific Salmon Commission on the 2017 Fraser River Sockeye and Pink Salmon fishing season. *In* Annual Reports of the Fraser River Panel to the Pacific Salmon Commission. Vancouver, BC. 1-79 p.

Pérez, M. J., Fernàndez, A. I. G., Rodriguez, L. A. and Nieto, T. P. 1996. Differential susceptibility to furunculosis of turbot and rainbow trout and release of the furunculosis agent from furunculosis-affected fish. Dis. Aquat. Org. 26: 133-137.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria..

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.

Reno, P. W. 1998. Factors involved in the dissemination of disease in fish populations. J. Aquat. Anim. Health 10(2): 160-171.

Roberts, R. J. 2012. The bacteriology of teleosts. *In* Fish Pathol. Wiley-Blackwell. pp 339-382.

Rose, A. S. 1990. Epidemiological aspects of *Aeromonas salmonicida* in the marine envrionment. Thesis (PhD) Institute of Aquaculture, University of Stirling. Stirling, Scotland. 229 p.

Rose, A. S., Ellis, A. E. and Munro, A. L. S. 1989. The infectivity by different routes of exposure and shedding rates of *Aeromonas salmonicida* subsp. *salmonicida* in Atlantic salmon, *Salmo salar* L., held in sea water. J. Fish Dis. 12: 573-578.

Rose, A. S., Ellis, A. E. and Munro, A. L. S. 1990a. Evidence against dormacy in the bacterial fish pathogen *Aeromonas salmonicida* subsp. *salmonicida*. FEMS Microbiol. Lett. 68(1-2): 105-107.

Rose, A. S., Ellis, A. E. and Munro, A. L. S. 1990b. The survival of *Aeromonas salmonicida* subsp. *salmonicida* in sea water. J. Fish Dis. 13(3): 205-214.

Rousseau, S., Gauthier, S., Johnson, S., Neville, C. and Trudel, M. 2017. Use of inverted echo-sounders to monitor the migration timing and abundance of juvenile salmon in the Discovery Islands, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 3227. viii + 33 p.

Smith, P. R., Brazil, G. M., Drinan, E. M., O'Kelly, J., Palmer, R. and Scallan, A. 1982. Lateral transmission of furunculosis in sea water. Bull. Eur. Assoc. Fish Pathol. 3: 41-42.

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. 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES J. Mar. Sci. 72(3): 997-1021.

USDA. 2014. Vaccines for aquaculture. Technical evaluation report.

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.

Ware, D. M. and McFarlane, G. A. 1989. Fisheries production domains in the northeast Pacific ocean. *In* Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. Beamish, R. J. and McFarlane, G. A. (eds.). Can. Spec. Publ. Fish. Aquat. Sci. 108: pp 359-379.

Wickham, H., Chang, W., Henry, L., Pedersen, T. L., Takahashi, K., Wilke, C. and Woo, K. 2018. Package 'ggplot2': Create Elegant Data Visualisations Using the Grammar of Graphics.

Wiklund, T. and Dalsgaard, I. 1998. Occurence and significance of atypical *Aeromonas salmonicida* in non-salmonid and salmonid fish species: a review. Dis. Aquat. Org. 32: 49-69.

Yi, M. M., Du, Y. S., Chi, L., Sun, G. X., Li, X. and Liu, Y. 2016. The impact of *Aeromonas salmonicida* infection on behaviour and physiology of Atlantic salmon (*Salmo salar* L.). Aquacult. Res. 47(7): 2287-2296.

Zetterberg, P. R. and Carter, E. W. 2010. Strait of Georgia sport fishery creel survey statistics for salmon and groundfish, 2008. Can. Manuscr. Rep. Fish. Aquat. Sci. 2929. xiv + 123 p.

Zetterberg, P. R., Watson, N. M. and O'Brian, D. S. 2012. Strait of Georgia recreational fishery statistics for salmon and groundfish, 2009. Can. Manuscr. Rep. Fish. Aquat. Sci. 2979. xii + 104 p.

9 APPENDICES

9.1 APPENDIX A: FISH HEALTH AUDIT AND SURVEILLANCE PROGRAM

This section summarizes the audit-based farm-level furunculosis diagnoses on Atlantic Salmon farms in the Discovery Islands area which includes all farms in Fish Health Surveillance Zone 3-2 and three farms in Fish Health Surveillance Zone 3-3 (Hardwicke, Althorpe and Shaw Point).

Between 2004 and 2016, there was on average 14 farms stocked per year, ranging from eight in 2013 to 18 in 2009 (Table 18). Between 2002 and 2016, 245 audits were conducted. From 2004 to 2011 between 25 and 88% of farms were audited annually. From 2012 to 2016, most active farms have been audited annually (80 to 100%).

Between 2002 and 2016, no audit-based farm-level diagnoses of furunculosis were reported on Atlantic Salmon farms in the Discovery Islands area.

Table 18. Summary of active Atlantic Salmon farms, number of audits conducted and audit-based farm-level furunculosis diagnoses on Atlantic Salmon farms located in the Discovery Islands area (Fish Health Surveillance Zone 3-2 and three farms in proximity in Fish Health Surveillance Zone 3-3) between 2002-2016. Number of active farms represents the total number of Atlantic Salmon farms with fish on site at any point in the year. Sources: DFO (2018c), data provided by DFO Aquaculture Management and the BC Salmon Farmers Association. NA: not available.

Year	Number of active farms	Number of audits	Number of farms audited	Percentage of farms audited	Number of audits with farm-level furunculosis diagnoses	Number of farms with farm-level furunculosis diagnoses
2002	NA	3	3	NA	0	0
2003	NA	10	4	NA	0	0
2004	14	13	9	64	0	0
2005	15	18	11	73	0	0
2006	16	19	12	75	0	0
2007	16	24	13	81	0	0
2008	17	28	15	88	0	0
2009	18	23	14	78	0	0
2010	16	4	4	25	0	0
2011	17	13	8	47	0	0
2012	13	23	12	93	0	0
2013	8	12	7	88	0	0
2014	10	16	8	80	0	0
2015	10	18	9	90	0	0
2016	11	21	11	100	0	0
Total	**---**	**245**	**---**	**---**	**0**	**0**

9.2 APPENDIX B: FISH HEALTH EVENTS ATTRIBUTED TO FURUNCULOSIS

This section summarizes the fish health events (FHEs) attributed to furunculosis on Atlantic Salmon farms in the Discovery Islands area.

Between 2004 and 2017, there was on average 14 active farms per year, ranging from eight in 2013 to 18 in 2009. Between 2002 and 2016, a total of 245 audits were conducted; most occurred in January (n=34) and the least in March (n=8) (Mimeault et al., 2020).

Between 2002 and the end of 2017, a total of six FHEs, on a total of six farms, were reported on Atlantic Salmon farms in the Discovery (Appendix A).

Table 19. Number of active Atlantic Salmon farms in the Discovery Islands area and fish health events (FHEs) attributed to furunculosis from 2002 to 2017. The number of active farms is the total number of Atlantic Salmon farms with fish on site at any point in the year. Sources: DFO (2018a), DFO Aquaculture Management and the BC Salmon Farmers Association. NA: data not available. Note that total number of farms (last line) represents the number of different farms.

Year	Number of active farms	Number of FHEs attributed to furunculosis	Number of farms that reported FHEs attributed to furunculosis
2002	NA	0	0
2003	NA	1	1
2004	14	0	0
2005	15	0	0
2006	16	0	0
2007	16	0	0
2008	17	0	0
2009	18	1	1
2010	16	2	2
2011	17	0	0
2012	13	0	0
2013	8	1	1
2014	10	0	0
2015	10	0	0
2016	11	0	0
2017	12	1	1
Total	**---**	**6**	**6**

9.3 APPENDIX C: INDUSTRY SURVEILLANCE AND SCREENING

Testing for non-fastidious bacterial pathogens, including *A. salmonicida*, by the industry is done through standard bacteriological procedures. All companies inoculate kidney samples taken from euthanized moribund fish and from fresh mortalities onto tryptone soy agar (TSA) plates for routine bacteriological screening. Other tissues, with or without lesions, are also sampled and cultured from such fish on an as-needed basis. Other culture media may also be used. Additional in-house procedures (bacterial subcultures of suspicious colonies, Gram staining, and biochemical tests) may be done to provide insight to identify a pathogen species, or the specimen may be sent to an external diagnostic laboratory for bacterial pathogen screening or identification. Although PCR assays are sensitive and useful to detect *A. salmonicida* (or its components) in a sample, bacterial cultures have the advantage to allow isolation and identification of strains involved (typical, atypical) as well as to determine the sensitivity of the isolates to antibiotics.

Aeromonas salmonicida has been occasionally found on Atlantic Salmon marine farms from the Discovery Islands area. Based on available industry data, *A. salmonicida* was reported in at least one sample from two farms in 2013, one farm in 2014, and one farm in 2017 (Table 20). These *A. salmonicida* detections occurred on three different farms; one of those farms having reported *A. salmonicida* infected fish in two different years.

Presumptive diagnosis of *A. salmonicida* is based on bacteriological cultures of kidneys (with or without additional tissues) on TSA plates (additional media may be used depending on each companies' procedures), followed by bacterial isolation and additional testing done in house or by an external diagnostic laboratory. Both typical (pigmenting) and atypical (non-pigmenting) strains have been reported by the industry. Bacteriological screening by industry occurred on all 18 Atlantic Salmon farms from the Discovery Islands area between 2011 and 2017.

Table 20. Summary of industry results of Aeromonas salmonicida *screening through bacteriological culture, histology and/or polymerase chain reaction (PCR) between 2011 and 2017 on Atlantic Salmon farms in the Discovery Islands area. No samples were determined positive for* A. salmonicida *on histology results alone.*

Year	Number of site visits with		Number of farms with	
	at least one positive sample (culture & PCR) for *A. salmonicida*	testing for *A. salmonicida*	at least one positive sample (culture, PCR) for *A. salmonicida*	testing for *A. salmonicida*
2011	0	19	0	11
2012	0	14	0	6
2013	2	8	2	7
2014	1	30	1	7
2015	0	9	0	6
2016	0	76	0	11
2017	5	49	1	10

9.4 APPENDIX D: *AEROMONAS SALMONICIDA* DISPERSION MODEL

The dispersion of *A. salmonicida* from marine Atlantic Salmon farms in the Discovery Islands area was modelled using the ocean circulation and particle dispersion and inactivation models by Foreman et al. (2012) and Foreman et al. (2015) with the following assumptions and calculations:

- Each of the farms was assumed to have the dimensions of 100 m by 100 m by 20 m (200,000 m^3).
- The model assumes that all 18 farms were infected and releasing *A. salmonicida* particles simultaneously;
- Thirty particles (cfu cohorts) were released every hour from random positions within each farm and tracked for a period of 26 days (representing the longest survival estimate for *A. salmonicida* from review by Boily et al. (2019)). The first release was at 0100 GMT on May 1st and the last was at 2300 on June 29th.
- The fractional survival of each cohort was computed for each hour of its tracking period. These survival rates were then "scaled-up" to actual cfu numbers based on shedding rates.
- Using the estimated shedding rate on the first day of infection, the scale-up factor under current fish health management practices was 1.96×10^9 for each cohort.
- Time varying *A. salmonicida* concentrations were computed at each of the approximately 65,000 elements in the circulation model grid as the number of cfu within each element horizontally and a prescribed depth range vertically. In light of the relatively low number of cohort releases (due to computer limitations) and their subsequent dispersion over the channels in the Discovery Islands area, concentration values were found to vary with the particular element areas.

9.5 APPENDIX E: PROPORTION OF POPULATION POTENTIALLY EXPOSED

This appendix details the estimation of the proportion of Fraser River Sockeye Salmon population, juveniles and adults, that could be in the Discovery Islands area at the same time as *A. salmonicida* infections and/or furunculosis have been reported on Atlantic Salmon farms.

These estimates assume that migrating fish would encounter the infected farm(s), i.e., fish would use the route(s) which have the infected farm(s). However, noting that there are routes through the Discovery Islands area where there are no Atlantic Salmon farms, and that location and number of simultaneously infected farms will be critical aspects in assessing actual exposure to infected farm(s), the following analysis provides an overestimate of the proportion of the population exposed to infected farms in the Discovery Islands area during periods when *A. salmonicida* infections and/or furunculosis were detected on one or more farms.

9.5.1 Juveniles

The proportion of juvenile Sockeye Salmon that could be exposed to *A. salmonicida*-infected farms in the Discovery Islands area during their migration was estimated based on:

- the out-migration timing of juvenile Fraser River Sockeye Salmon; and
- the weighted number of months with evidence of *A. salmonicida* infection during which juveniles could encounter infected farms each year between 2002 and 2017.

Juvenile lake-type Fraser River Sockeye Salmon tend to migrate through the Discovery Islands area from mid-May to mid-July, with peak catches in early-to-mid June (Grant et al., 2018). Raw data from a study conducted by Freshwater et al. (2019), from mid-May to mid-July over three years (2014-2016) of out-migration of Fraser River Sockeye Salmon were used to calculate the temporal distribution of captured juveniles around the Discovery Islands area. According to this dataset, 30%, 62% and 8% of juveniles were captured in May, June and July, respectively, which is in agreement with other studies indicating Fraser River Sockeye Salmon outmigration peak occurs in June around the Discovery Islands area (Neville et al., 2016; Grant et al., 2018).

These three percentages were then applied as frequency weights to (i.e., multiplied by) each corresponding monthly infection status within any given year, between 2002 and 2017 (Table 21). For instance, in 2009, May had infected farms and received its respective weight of 30% but June and July were uninfected (zero). Therefore, the sum of the three weighted-months resulted in an estimate of the proportion of juveniles that could potentially have been in the Discovery Islands area at the time of an infection in this year to be 30%.

Table 21. Estimated proportion of juvenile lake-type Fraser River Sockeye Salmon that could potentially have been exposed to Aeromonas salmonicida*-infected Atlantic Salmon farm(s) during their migration through the Discovery Islands area between 2002 and 2017. Presence (1) or absence (0) of infection on farms are the binary representation of data from Table 11. Weighted presence/absence are the presence/absence multiplied by the temporal distribution of juveniles through the Discovery Islands area (30% for May, 62% for June and 8% for July). The proportion of juvenile potentially exposed is the sum of the weighted presence/absence (May to July).*

Year	Presence (1) / absence (0)			Weighted presence/absence			Proportion of juveniles potentially exposed
	May	June	July	May	June	July	
2002	0	0	0	0.00	0.00	0.00	0.00
2003	0	0	0	0.00	0.00	0.00	0.00
2004	0	0	0	0.00	0.00	0.00	0.00
2005	0	0	0	0.00	0.00	0.00	0.00
2006	0	0	0	0.00	0.00	0.00	0.00
2007	0	0	0	0.00	0.00	0.00	0.00
2008	0	0	0	0.00	0.00	0.00	0.00
2009	1	0	0	0.30	0.00	0.00	0.30
2010	0	0	0	0.00	0.00	0.00	0.00
2011	0	0	0	0.00	0.00	0.00	0.00
2012	0	0	0	0.00	0.00	0.00	0.00
2013	0	1	0	0.00	0.62	0.00	0.62
2014	0	1	0	0.00	0.62	0.00	0.62
2015	0	0	0	0.00	0.00	0.00	0.00
2016	0	0	0	0.00	0.00	0.00	0.00
2017	0	0	0	0.00	0.00	0.00	0.00

With the evidence of *A. salmonicida* on Atlantic Salmon farms in the Discovery Islands area and the weighted frequency distribution based on the timing of migration, the proportion of juvenile Fraser River Sockeye Salmon that could have been in the Discovery Islands area when *A. salmonicida* was released from Atlantic Salmon farms between 2002 and 2017 (16 years) in the Discovery Islands area ranged between 0 and 62% (median=0% and mean=10%).

However, in the consequence assessment, the years without evidence of infection (total of 13 years) have to be disregarded given the assumption that “at least one migratory fish has been infected with the *A. salmonicida* released from an infected farm/s.” When only considering years with evidence of infection while juveniles were migrating through the area between 2002 and 2017 (three years), the proportion of juvenile Fraser River Sockeye Salmon that could have been in the Discovery Islands area when *A. salmonicida* was released from Atlantic Salmon farms ranged between 30 and 62% (median=62% and mean=51%). These estimates are based on the evidence of *A. salmonicida* occurrences summarized in Table 11.

9.5.2 Adults

The proportion of adult Sockeye Salmon that could be exposed to *A. salmonicida*-infected farms in the Discovery Islands area during their return migration to the Fraser River (Table 22) was estimated based on:

- Northern diversion rates (NDR) of returning adult Fraser River Sockeye Salmon ranging from 10 to 96% between 2002 and 2017 (Pacific Salmon Commission data presented in Grant et al. (2018) and 2016 and 2017 reports of the Fraser River Panel to the Pacific Salmon Commission (Pacific Salmon Commission, 2017, 2018)); and
- the weighted number of months with evidence of *A. salmonicida* infections from June to October (when adults are in the Discovery Islands area) between 2002 and 2017.

Returning adult Fraser River Sockeye Salmon tend to migrate through the Discovery Islands area from late-June to early-October (Grant et al., 2018). Estimates of the temporal distribution of returning adults in the Discovery Islands area were based on data provided by the Pacific Salmon Commission. Daily estimates (2003-2017) of the marine abundance of returning Fraser River Sockeye Salmon based on Mission hydro acoustics data including all catches below Mission for the four management groups (Early Stuart, Early Summer, Summer, and Late) were provided by the Pacific Salmon Commission. Dates were offset based on assumed migration speed to account for the time-lag in migration between the Discovery Islands area and Mission.

The abundance estimates were summed up over all management groups by year. Within each year, the summed values were multiplied by their corresponding annual NDR, resulting in abundance estimates for Fraser River Sockeye Salmon migrating through the Discovery Islands region. Finally, all daily estimates were aggregated over the 16 years and the relative frequency distribution of fish per in-migration month through the Discovery Islands area (June-September available) was calculated. Given that test fisheries do not take in place October, the relative frequency for October was determined to be zero. However, 0.1% relative frequency was assigned to the month of October (conservative estimate) to account for the very small number of fish typically reported early October in the region. Based on this dataset, 0.3%, 12.2%, 79.7%, 7.7% and 0.1% of returning adults are expected in the Discovery Islands area in the months of June, July, August, September and October, respectively.

These five percentages were then applied as frequency weights to (i.e., multiplied by) each corresponding monthly infection within any given year, between 2002 and 2017 (Table 11). For instance, in 2017, August, September and October had infected farms and therefore received their respective weights of 79.7%, 7.7% and 0.1% but June and July were not infected (zero). Therefore, the sum of the five weighted-months (87.5%) multiplied by the NDR for the year (71%) resulted in an estimate of the proportion of adults that could potentially have been exposed in this year to be 62% (Table 22).

Table 22. Estimated proportion of adult Fraser River Sockeye Salmon that could potentially have been exposed to Aeromonas salmonicida-*infected Atlantic Salmon farm(s) during their migration through the Discovery Islands area between 2002 and 2017. Northern diversion rates (NDR) are from data summarized in Grant et al. (2018) and from Pacific Salmon Commission (2017, 2018). Presence (1) or absence (0) of infection on farms are the binary representation of data from Table 11. Weighted presence/absence are presence/absence multiplied by the temporal distribution of returning adults through the Discovery Islands area (0.3%, 12.2%, 79.7%, 7.7% and 0.1% in June through October, respectively, based on all catches below Mission offset to account for the time-lag migration from the Discovery Islands area). The proportion of the adults potentially exposed is the sum of weighted presence/absence (June to October) multiplied by the NDR.*

Year	Presence (1) / absence (0)					Weighted presence/absence					Sum weighted presence/ absence	NDR	Proportion of adults potentially exposed
	Jun	Jul	Aug	Sep	Oct	Jun	Jul	Aug	Sep	Oct			
2002	0	0	0	0	0	0	0	0	0	0	0	0.51	0
2003	0	0	0	0	0	0	0	0	0	0	0	0.69	0
2004	0	0	0	0	0	0	0	0	0	0	0	0.64	0
2005	0	0	0	0	0	0	0	0	0	0	0	0.74	0
2006	0	0	0	0	0	0	0	0	0	0	0	0.65	0
2007	0	0	0	0	0	0	0	0	0	0	0	0.44	0
2008	0	0	0	0	0	0	0	0	0	0	0	0.10	0
2009	0	0	0	0	0	0	0	0	0	0	0	0.47	0
2010	0	0	0	0	0	0	0	0	0	0	0	0.73	0
2011	0	0	0	0	0	0	0	0	0	0	0	0.62	0
2012	0	0	0	0	0	0	0	0	0	0	0	0.18	0
2013	1	0	0	0	0	0.003	0	0	0	0	0.003	0.71	0.002
2014	1	0	0	0	0	0.003	0	0	0	0	0.003	0.96	0.003
2015	0	0	0	0	0	0	0	0	0	0	0	0.69	0
2016	0	0	0	0	0	0	0	0	0	0	0	0.50	0
2017	0	0	1	1	1	0	0	0.797	0.077	0.001	0.875	0.71	0.621

The proportion of returning adult Fraser River Sockeye Salmon that could have been in the Discovery Islands area when *A. salmonicida* was released from Atlantic Salmon farms between 2002 and 2017 (16 years) during their returning migration in the Discovery Islands area ranged between 0 and 62.1% (median=0% and mean= 3.9%).

When only considering the three years with evidence of infection on farm(s) while adults were migrating through the area between 2002 and 2017, the proportion of returning adult Fraser River Sockeye Salmon that could have been in the Discovery Islands area when *A. salmonicida* was released from Atlantic Salmon farms during their return migration ranged between 0.2% and 62% (median=0.3% and mean= 20.9%). These estimates are based on evidence of *A. salmonicida* occurrences including detections at the fish level summarized in Table 11.

9.6 APPENDIX F: EXPOSURE OVER TWO GENERATIONS

The potential exposure of Fraser River Sockeye Salmon populations to Atlantic Salmon farms infected with *A. salmonicida* over two generations (eight years for Fraser River Sockeye Salmon) was estimated to explore potential impacts on diversity.

9.6.1 Binomial process approach

There are two possible exposure outcomes in any given year for migrating Fraser River Sockeye Salmon, i.e., migrating salmon can be exposed (success outcome) or not (failure outcome). Given the two possible outcomes, the number of successes (s) over a given number of trials (n) can be estimated using the binomial process.

The exposure assessment determined that between 2002 and 2017, three years reported evidence of *A. salmonicida* and/or furunculosis during the months when Fraser River Sockeye Salmon (juveniles or adults) are expected in the Discovery Islands area (Table 11). In other words, in any given year, the probability that Fraser River Sockeye Salmon could be in the Discovery Islands area at the same time as a farm is infected with *A. salmonicida* is, on average, 18.75% (3/16) for both juveniles and adults.

Assuming that (i) the probability of exposure each year is independent of the previous one and (ii) there is a constant probability of exposure each year, a binomial distribution was conducted in R with the following input parameters:

- probability of success (P) = 0.1875 for juveniles or adults, and
- number of trials (n) = eight years, representing two generations of Fraser River Sockeye Salmon.

The potential that juveniles or adults are in the Discovery Islands area at the same time as an infection with *A. salmonicida* on an Atlantic Salmon farm, based on the binomial process explained above is:

- On average, 1.5 years out of the eight years (mean = n × P = 8 × (3/16) = 1.5, with SD = $\sqrt{n \times p \times (1-p)}$ = 1.1).
- Figure 8 provides the complementary cumulative binomial probability distribution (CCDF), from which the probability of exposure in at least a given number of years is illustrated. For example, the probability that juveniles (or adults) become exposed in at least two out of eight years is 46%, while the probability that juveniles (or adults) become exposed in at least five out of eight years is 1%, and so on.
- Over one generation (four years), the probability of exposure in four consecutive years is 0.12% (P^4 = 0. 1875^4 = 0.0012).

- Over two generations, the probability of exposure in at least four consecutive years over eight years is determined by the sum of the products of the probabilities of exposure over at least four years and the probabilities for those years to be consecutive. Consequently, the probability that juveniles or adults could be exposed to *A. salmonicida* released from infected Atlantic Salmon farms in the Discovery Islands area in at least four consecutive years over two generations is 0.33% (Table 23).

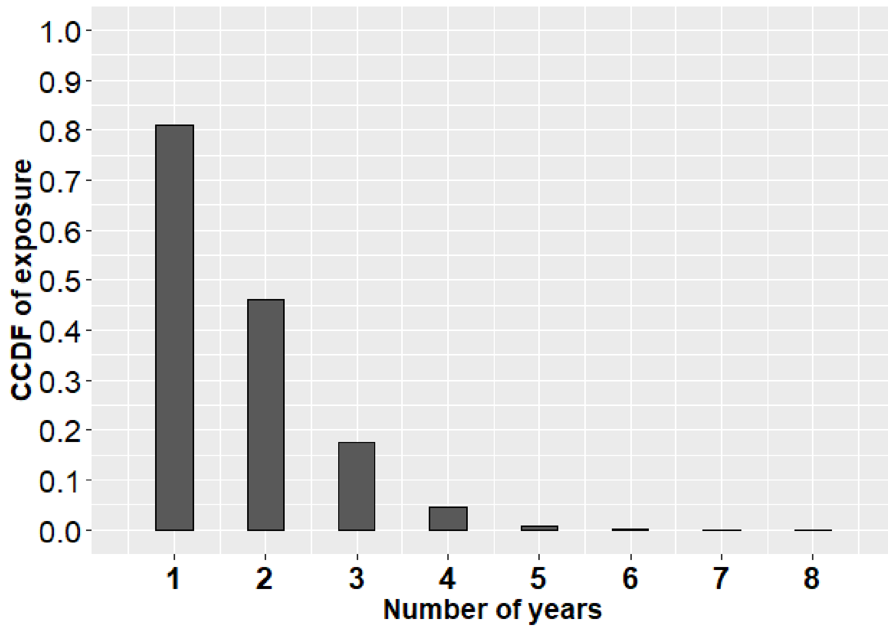

Figure 8. Complementary cumulative probability distribution (CCDF) of potential exposure of juvenile or adult Fraser River Sockeye Salmon to Aeromonas salmonicida*-infected Atlantic Salmon farms in the Discovery Islands area over eight years. The probability of exposure is based on a binomial process assuming a probability of success (p) of 0.1875, and a number of trials (n) of eight years.*

Table 23. Probability of exposure of juvenile and adult Fraser River Sockeye Salmon to Aeromonas salmonicida *attributable to Atlantic Salmon farms in the Discovery Islands area in at least four consecutive years over a time period representing two generations (eight years). The probability of exposure is based on a binomial process assuming the probability of success (P) on an individual trial (year) is 0.1875 and the number of trials (n) is eight.*

(a) Number of success (x): number of years with exposure	(b) Number of trials (n): number of years for two generations	(c) Binomial probability: P(X = x) (exactly x successes in n trials)	(d) Number of consecutive combinations of x in n *	(e) Number of distinct combinations of x in n **	(f) Probability of exactly x consecutive years in n years (c × d / e)
4	8	0.0377	5	70	0.0027
5	8	0.0070	4	56	0.0005
6	8	0.0008	3	28	8.6×10^{-5}
7	8	5.3×10^{-5}	2	8	1.3×10^{-5}
8	8	1.5×10^{-6}	1	1	1.5×10^{-6}
Probability of at least four consecutive years in two generations (eight years)					**0.0033**

* *For example, with x=4 and n=8: 1-2-3-4; 2-3-4-5; 3-4-5-6; 4-5-6-7; and 5-6-7-8.*
** *For example, with x=4 and n=8: 1-2-3-4; 1-2-3-5; 2-4-6-7; 4-5-7-8; ...; for a total of 70 combinations.*

9.6.2 Simulation approach

To further evaluate the reliability of the exposure estimates from the binomial process, a simulation approach was undertaken. To do this, a bootstrap sampling strategy was used to randomly select eight years out of the 16 years of assessment (0: year without infection, 1: year with infection) with 1,000 and 10,000 iterations. The sum of infected years (per iteration) was calculated for each iteration to estimate the number of years during which juveniles and adults could be expected to migrate through the Discovery Islands area while there would be at least one Atlantic Salmon farm infected with *A. salmonicida* and/or showing clinical signs of furunculosis.

The resulting frequency distributions of the sums were compared to the results of the binomial process (Table 24). The two approaches produced very close results, supporting the reliability of the approaches in estimating the potential exposure of Fraser River Sockeye Salmon over eight years. As the number of iterations increased (e.g., from 1,000 to 10,000), the bootstrap distribution resembled the binomial distribution (see Table 24 for examples).

Table 24. Comparison of the exposure estimates from the binomial process and bootstrapping (1,000 and 10,000 iterations). Each percentage represents the probability of exposure of juvenile or adult Fraser River Sockeye Salmon in at least a given number of years (out of eight).

Years of infection	Method	Juveniles or adults (%)
At least three	Binomial process	~17
	Bootstrap (1,000)	~16
	Bootstrap (10,000)	~17
At least six	Binomial process	~0
	Bootstrap (1,000)	~0
	Bootstrap (10,000)	~0

9.7 APPENDIX G: MODELLING THE SPREAD OF *AEROMONAS SALMONICIDA* INFECTION IN WILD FRASER RIVER SOCKEYE SALMON

A stochastic, frequency-dependent compartmental susceptible-exposed-infected-recovered (SEIR) model with disease-induced mortality (Figure 9) was built to explore the conditions under which *A. salmonicida* could spread in the adult wild Sockeye Salmon population. A frequency-dependent model was chosen because it represents the behaviour of schooling fish better than a density-dependent model. In a frequency-dependent model, the number of contacts is independent of population size, i.e., as population size decreases (mainly from disease-induced mortality) it effectively occupies a smaller area and therefore an individual fish is in no closer contact with its nearest neighbour in a large school than in a small school. However, this does not mean that density does not affect the dynamics of *A. salmonicida* transmission (Boily et al., 2019).

The model categorizes hosts in the population in one of five compartments: susceptible (if non-immune or previously unexposed to *A. salmonicida*), exposed (if infected but not yet infectious), infected (if infected and able to transmit the pathogen to susceptible hosts), and recovered (if they have successfully cleared the infection and acquired immunity). There are two infected compartments Y_1 and Y_2. Individuals in both compartments are able to transmit the pathogen to susceptible hosts, but recovery and disease-induced mortality can only occur from the Y_2compartment.

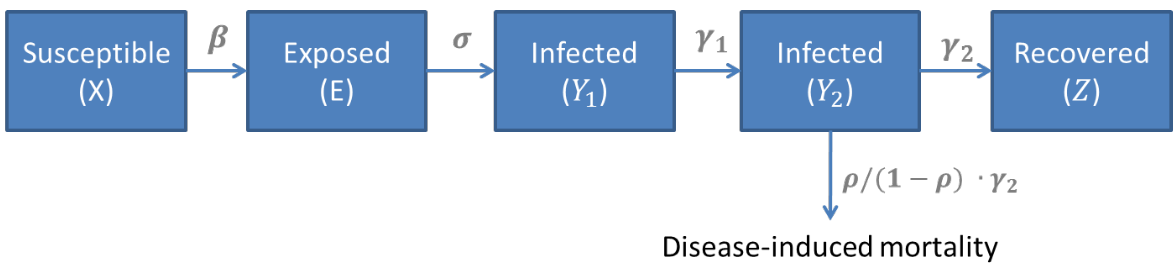

Figure 9. Frequency-dependent compartmental susceptible-exposed-infected-recovered (SEIR) model with disease-induced mortality.

Where X, E, Y and Z are the number of susceptible, exposed, infected and recovered fish, respectively; β is the transmission parameter, σ is the rate of transition from exposed to infected ($1\,/\,\sigma$ is the average length of the latent period), γ is the recovery rate and ρ is the probability of dying from infection prior to recovery. The total number of fish in the population, N, is:

$$N = X + E + Y_1 + Y_2 + Z \qquad (1)$$

The transmission parameter β can be expressed as:

$$\beta = R_0 \cdot \gamma \qquad (2)$$

where R_0 is the basic reproductive ratio and $1\,/\,\gamma$ is the average length of the infected period.

Fish move from the infected compartment Y_1 to the infected compartment Y_2 at rate γ_1, and recover from infection at rate γ_2. The average length of the infectious period is represented by:

$$\frac{1}{\gamma} = \frac{1}{\gamma_1} + \frac{1}{\gamma_2} \qquad (3)$$

The average length of time between exposure and the start of disease-induced mortality, Φ, can be expressed as:

$$\Phi = \frac{1}{\sigma} + \frac{1}{\gamma_1} \quad (4)$$

The mathematical model can be described by the equations (5) to (9) below, adapted from sections 2.2., 2.5 and 3.3 in Keeling and Rohani (2007).

Equation (5) represents the change in the number of susceptible individuals, as fish are removed from the susceptible compartment to enter the exposed compartment. It is dependent on the transmission parameter β as well as on the proportion of infectious individuals in the population.

$$\frac{dX}{dt} = -\beta \cdot X \cdot \frac{(Y_1 + Y_2)}{N} \quad (5)$$

The first part of Equation (6) represents the fish that enter the exposed compartment from the susceptible compartment whereas the second part represents the fish that are removed from the exposed compartment to enter the first infected compartment Y_1. This transition is dependent on the average length of the latent period.

$$\frac{dE}{dt} = \beta \cdot X \cdot \frac{(Y_1 + Y_2)}{N} - \sigma \cdot E \quad (6)$$

The first part of Equation (7) represents the fish that enter the first infected compartment from the exposed compartment whereas the second part represents the fish that are removed from the first infected compartment to enter the second infected compartment Y_1. This transition is dependent on the average length of the infectious period and on the average length of time between exposure and the start of disease-induced mortality.

$$\frac{dY_1}{dt} = \sigma \cdot E - \gamma_1 \cdot Y_1 \quad (7)$$

The first part of Equation (8) represents the fish that enter the second infected compartment from the first infected compartment, the second part represents the fish that are removed from the second infected compartment to enter the recovered compartment, and the third part represents the fish that die from the disease prior to recovery. This transition is dependent on the average length of the infectious period, on the average length of time between exposure and the start of disease-induced mortality, and on the probability of dying prior to recovery.

$$\frac{dY_2}{dt} = \gamma_1 \cdot Y_1 - \gamma_2 \cdot Y_2 - \frac{\rho}{(1-\rho)} \cdot \gamma_2 \cdot Y_2 \quad (8)$$

Equation (9) represents the fish that enter the recovered compartment from the second infected compartment. This transition is dependent on the average length of the infectious period, and on the average length of time between exposure and the start of disease-induced mortality.

$$\frac{dZ}{dt} = \gamma_2 \cdot Y_2 \quad (9)$$

Stochastic simulations were conducted using the τ-leap algorithm with a fixed daily time step (Gillespie and Petzold, 2003; Keeling and Rohani, 2007). All models, analyses, and simulations were done using R version 3.5.1 (R Core Team, 2018), using the ggplot2 package for graphics representations (Wickham et al., 2018).

Because the parameters required in the model are unknown for wild Sockeye Salmon, assumptions were made and different combinations of model parameters were compared. One thousand iterations were run for each combination of model parameters.

Assumptions used in this model include:

- All returning adult Sockeye Salmon migrate at the same time
- All fish have the same probability of contact between each other
- Dead fish are not a source of infectious pathogen
- There is no local accumulation of pathogen in the water
- Natural mortality is not represented in the model
- Initially, all fish are completely susceptible *to Aeromonas salmonicida* infection
- Recovered fish have lifelong immunity
- A single infected fish is introduced in a population of one million fish at day 0

The parameters for the SEIR model were based on laboratory experiments conducted with Chinook Salmon fry exposed to *A. salmonicida* by co-habitation in freshwater (Ogut, 2001; Ogut and Reno, 2004; Ogut et al., 2004; Ogut et al., 2005; Ogut and Reno, 2005).

In the first scenario, the following combination of parameters was used: R_0= 3.25 in 1.97 g Chinook Salmon in freshwater at a density of 5,700 fish/m^3 (Ogut et al., 2004); ρ = 64% (based on mortality rate of infected individuals at 10 days post-exposure in Ogut et al. (2004)), average duration of the latent period $1 / \sigma$ = 3 days (Ogut, 2001), average total duration of the infectious period $1 / \gamma$ = 14 days (Enger et al., 1992) and average duration of the period between exposure and disease-induced mortality Φ = 9 days (estimated from data in Ogut et al. (2004)).

Figure 10 shows that under these conditions, disease-induced mortality starts increasing slowly around 70 days post-exposure (dpe) and raises to 1% of the population on average at 120 dpe (minimum = 94 dpe). This was compared to the length of time required for adult Fraser River Sockeye Salmon to reach their spawning grounds after they pass through the Discovery Islands area and enter the Fraser River. For most fish, this takes approximately 35 days, after which they spawn and die. Therefore, it is expected that the fish will die of natural causes before the pathogen can spread widely enough in the population in order to cause significant mortality at the population level. Moreover, when the number of initially infected individuals is small, such as here, extinction of the outbreak prior to the logarithmic phase of growth is possible, due to the stochasticity of the process (Allen et al., 2017). Under the conditions modelled, in 32% of the 1,000 iterations of the model, there was no significant spread of infection, i.e., less than 1% cumulative mortality over 365 days.

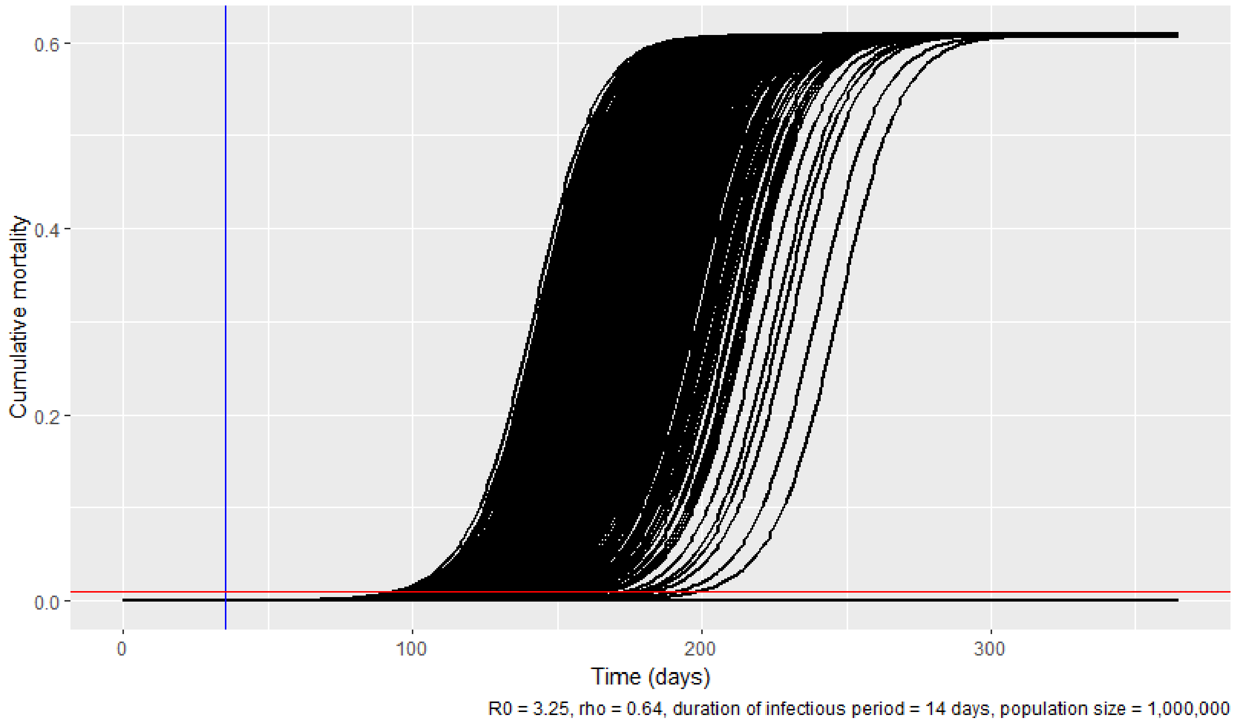

Figure 10. Cumulative mortality resulting from simulated spread of Aeromonas salmonicida *in the returning adult Sockeye Salmon population. Model ran with 1,000 iterations and a single infected fish introduced in a population of one million fish at day 0. The blue line indicates the time when most returning adults will have reached their spawning grounds and died. The red line represents one percent cumulative mortality.*

Using the same parameters as above, it was determined that an $R_0 \geq 12$ would be required in order to see a significant proportion of the population (1%) dying within 35 days post exposure. Even by changing other parameters to sometimes unrealistic values, it was not possible to reach 1% cumulative mortality within 35 days with values of $R_0 \leq 7$. It is extremely unlikely that the basic reproductive ratio of *A. salmonicida* would be this high in wild salmon. Indeed, it is generally accepted that diseases with a basic reproductive ratio of 5 or higher are very contagious: in a well-mixed and completely susceptible population, almost all individuals are likely to contract the disease (Keeling and Rohani, 2007). As an example, the basic reproductive ratio of foot-and-mouth disease, which is often considered the most contagious disease of cattle, was estimated at 3.5-4.5 during the 2001 outbreak in Great Britain (Ferguson et al., 2001).

Using the same parameters as above, the number of initially infected fish that would be required in order to see a significant proportion of the population (1%) dying within 35 days post exposure was also explored. At $R_0 = 3.25$, one thousand initially infected fish would be required; at $R_0 = 5$, four hundred initially infected fish; and at $R_0 = 8$, approximately 50 initially infected fish would be required. However, given the conclusions of the infection assessment, and given the discussion on the basic reproductive ratio in the above paragraph, these conditions are extremely unlikely to be present.