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Assessment of the risk to Fraser River Sockeye Salmon due to *Renibacterium salmoninarum* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia

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Foreword

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

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TABLE OF CONTENTS

LIST OF TABLES V
LIST OF FIGURES VII
GLOSSARY VIII
ABSTRACT IX
1 INTRODUCTION 1
2 BACKGROUND 1
2.1 MANAGEMENT PROTECTION GOALS 2
2.2 PROBLEM FORMULATION 2
2.2.1 Hazard identification 2
2.2.2 Hazard characterization 2
2.2.3 Scope 2
2.2.4 Risk question 4
2.2.5 Methodology 4
3 LIKELIHOOD ASSESSMENT 8
3.1 FARM INFECTION ASSESSMENT 8
3.1.1 Question 8
3.1.2 Considerations 8
3.1.3 Assumptions 16
3.1.4 Likelihood of farm infection 16
3.2 RELEASE ASSESSMENT 17
3.2.1 Question 17
3.2.2 Considerations 17
3.2.3 Assumptions 18
3.2.4 Likelihood of release 18
3.3 EXPOSURE ASSESSMENT 20
3.3.1 Question 20
3.3.2 Considerations 20
3.3.3 Assumptions 25
3.3.4 Likelihood of exposure 25
3.4 INFECTION ASSESSMENT 27
3.4.1 Question 27
3.4.2 Considerations 27
3.4.3 Assumptions 32
3.4.4 Likelihood of infection 32
3.5 OVERALL LIKELIHOOD ASSESSMENT 33
4 CONSEQUENCE ASSESSMENT 34
4.1 QUESTION 34
4.2 CONSIDERATIONS 34

4.2.1 *Renibacterium salmoninarum* infection dynamics 34
4.2.2 Prevalence of infection in wild Pacific salmonid populations 34
4.2.3 Bacterial kidney disease mortality in wild Sockeye Salmon....35
4.2.4 Subclinical infections with *Renibacterium salmoninarum* 36
4.2.5 Estimates of Fraser River Sockeye Salmon densities 36
4.2.6 Estimates of the proportion potentially exposed to infected farms....37
4.2.7 Estimates of exposure over two generations....38
4.3 ASSUMPTIONS....39
4.4 MAGNITUDE OF CONSEQUENCES 39
4.4.1 Juvenile Fraser River Sockeye Salmon....39
4.4.2 Adult Fraser River Sockeye Salmon 40
4.4.3 Other susceptible Pacific salmon species 41
5 RISK ESTIMATION....41
5.1 ABUNDANCE 41
5.2 DIVERSITY....42
6 SOURCES OF UNCERTAINTIES 42
6.1 LIKELIHOOD ASSESSMENT 43
6.2 CONSEQUENCE ASSESSMENT....43
7 CONCLUSIONS....43
8 REFERENCES CITED 44
9 APPENDICES 50
9.1 APPENDIX A: FISH HEALTH AUDIT AND SURVEILLANCE PROGRAM 50
9.2 APPENDIX B: FISH HEALTH EVENTS 54
9.3 APPENDIX C: INDUSTRY SURVEILLANCE AND DETECTIONS 55
9.4 APPENDIX D: PROPORTION OF POPULATION POTENTIALLY EXPOSED....56
9.4.1 Juveniles....56
9.4.2 Adults 57
9.5 APPENDIX E: EXPOSURE OVER TWO GENERATIONS....60
9.5.1 Binomial process approach....60
9.5.2 Simulation approach 63

LIST OF TABLES

Table 1. List of the 18 active Atlantic Salmon farms included in the risk assessment. 4

Table 2. Categories and definitions used to describe the likelihood of an event over a period of a year.. 5

Table 3. Categories and definitions used to describe the potential consequences to the abundance of Fraser River Sockeye Salmon. 6

Table 4. Categories and definitions used to describe the potential consequences to the diversity of Fraser River Sockeye Salmon.. 6

Table 5. Categories and definitions used to describe the level of uncertainty associated with data and information. 6

Table 6. Categories and definitions used to describe the level of uncertainty associated with fish health management. 7

Table 7. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of *Renibacterium salmoninarum* infection and/or bacterial kidney disease (BKD) summarized by year...15

Table 8. Factors contributing to and limiting the likelihood that farmed Atlantic Salmon infected with *Renibacterium salmoninarum* are present on one or more Atlantic Salmon farms in the Discovery Islands area under the current fish health management practices. 16

Table 9. Factors contributing to and limiting the likelihood that *Renibacterium salmoninarum* will be released from infected and/or diseased Atlantic Salmon on farms in the Discovery Islands area under the current farm practices. 19

Table 10. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of *Renibacterium salmoninarum* and/or bacterial kidney disease (BKD) summarized by month....24

Table 11. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of *Renibacterium salmoninarum* and/or bacterial kidney disease (BKD) summarized per year and month...25

Table 12. Factors contributing to and limiting the likelihood that Fraser River Sockeye Salmon and other susceptible Pacific salmon species would be exposed to *Renibacterium salmoninarum* released from infected/diseased Atlantic Salmon farm(s) in the Discovery Islands area under the current fish health management practices..26

Table 13. Factors contributing to and limiting the likelihood that Fraser River Sockeye Salmon and other susceptible Pacific salmon species would become infected with *Renibacterium salmoninarum* released from infected Atlantic Salmon farms in the Discovery Islands area under current fish health management practices...32

Table 14. Summary of the likelihood and uncertainty rankings in the *Renibacterium salmoninarum* risk assessment. 33

Table 15. Risk estimates to the abundance of Fraser River Sockeye Salmon resulting from *Renibacterium salmoninarum* attributable to Atlantic Salmon farms located in the Discovery Islands area under current farm management practices..42

Table 16. Risk estimates to the diversity of Fraser River Sockeye Salmon resulting from *Renibacterium salmoninarum* attributable to Atlantic Salmon farms located in the Discovery Islands area under current farm management practices..42

Table 17. Summary of active Atlantic Salmon farms, number of audits conducted and audits with farm-level bacterial kidney disease (BKD) 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. 50

Table 18. Results of government fish health audits (2002-2016) conducted on Atlantic Salmon farms in the Discovery Islands area in which *Renibacterium salmoninarum* and/or bacterial kidney disease (BKD) were detected. 52

Table 19. Number of active Atlantic Salmon farms in the Discovery Islands area and fish health events (FHEs) attributed to bacterial kidney disease (BKD) from 2002 to 2017......................... 54

Table 20. Summary of industry *Renibacterium salmoninarum* detections and/or bacterial kidney disease (BKD) diagnoses between 2011 and 2017 on Atlantic Salmon farms in the Discovery Islands area. 55

Table 21. Estimated proportion of juvenile lake-type Fraser River Sockeye Salmon that could potentially have been exposed to *Renibacterium salmoninarum*-infected Atlantic Salmon farm(s) during their migration through the Discovery Islands area between 2002 and 2017. 57

Table 22. Estimated proportion of adult Fraser River Sockeye Salmon that could potentially have been exposed to *Renibacterium salmoninarum*-infected Atlantic Salmon farm(s) during their migration through the Discovery Islands area between 2002 and 2017. 59

Table 23. Probability of exposure of juvenile Fraser River Sockeye Salmon to *Renibacterium salmoninarum* 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). 61

Table 24. Probability of exposure of adult Fraser River Sockeye Salmon to *Renibacterium salmoninarum* 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 0.8125 and the number of trials (n) is eight. 63

Table 25. Comparison of the exposure estimates from the binomial process and bootstrapping (1,000 and 10,000 iterations). 63

LIST OF FIGURES

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. 3

Figure 2. Conceptual model to assess the risks to Fraser River Sockeye Salmon resulting from *Renibacterium salmoninarum* attributable to Atlantic Salmon farms located in the Discovery Islands area, British Columbia. 5

Figure 3. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon abundance. 8

Figure 4. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon diversity. 8

Figure 5. Estimated maximum waterborne concentration (cfu/m^3) for *Renibacterium salmoninarum* on an infected Atlantic Salmon farm in the Discovery Islands area, BC. 31

Figure 6. Potential outcomes resulting from at least one susceptible wild fish infected with *Renibacterium salmoninarum* released from Atlantic Salmon farms located in the Discovery Islands area. 39

Figure 7. Complementary cumulative probability distribution (CCDF) of potential exposure of juvenile Fraser River Sockeye Salmon to *Renibacterium salmoninarum*-infected Atlantic Salmon farms in the Discovery Islands area over eight years. 61

Figure 8. Complementary cumulative probability distribution (CCDF) of potential exposure of adult Fraser River Sockeye Salmon to *Renibacterium salmoninarum*-infected Atlantic Salmon farms in the Discovery Islands area over eight years. 62

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

Incubation period: The 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 *Renibacterium salmoninarum* 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 fish, and infection of susceptible fish); second, a consequence assessment; and third, a risk estimation which combines the first two steps.

Renibacterium salmoninarum, the causative agent of bacterial kidney disease, is endemic to BC where it has been detected both in wild and farmed salmon. Based on evidence of infection and disease reported on Atlantic Salmon farms between 2002 and 2017, it is very likely, with reasonable certainty, that farmed Atlantic Salmon in the Discovery Islands area will become infected with *R. salmoninarum* in any given year under the current farm practices. Although the shedding rates from *R. salmoninarum*-infected Atlantic Salmon have not been quantified, it is extremely likely, with high certainty, that *R. salmoninarum* would be released from infected Atlantic Salmon because it is naturally shed from the body into the surrounding environment. Given temporal overlap of *R. salmoninarum* infections on farms and Fraser River Sockeye Salmon migration through the Discovery Islands area, it is very likely, with reasonable certainty, that at least one juvenile and returning adult will be exposed in any given year. Under such exposure, however, it is extremely unlikely, with reasonable uncertainty, that juveniles or adults would get infected, as the estimated waterborne concentration of *R. salmoninarum* on Atlantic Salmon farms is approximately 1/125th of the lowest dose reported to cause infection in Chinook Salmon (*O. tshawytscha*). Overall, it was concluded that it is extremely unlikely that Fraser River Sockeye Salmon would become infected with *R. salmoninarum* released from Atlantic Salmon farms in the Discovery Islands area under current farm practices.

The potential magnitude of consequences to the abundance and diversity of Fraser River Sockeye Salmon was determined to be negligible, with reasonable uncertainty, for both juveniles and adults given that an infection acquired at the juvenile stage would be not expected to spread and an infection acquired at the adult stage would not be expected to develop before reaching spawning grounds.

Overall, the assessment concluded that *R. salmoninarum* attributable to Atlantic Salmon farms in the Discovery Islands area poses minimal risk to Fraser River Sockeye Salmon abundance and diversity under the current farm practices. Conclusions have been reached based on a series of rankings estimated with a range of uncertainties. The 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 *Renibacterium salmoninarum*, the causative agent of bacterial kidney disease (BKD), 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 BKD had been reported at the farm level on Atlantic Salmon farms in the Discovery Islands area.

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 *R. salmoninarum* attributable to Atlantic Salmon farms in the Discovery Islands area.

2.2.2 Hazard characterization

Rhodes and Mimeault (2019) reviewed the relevant characteristics of *R. salmoninarum* and BKD (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 *R. salmoninarum* and BKD on Atlantic Salmon farms in BC. Additional details specific to Atlantic Salmon farms located in the Discovery Islands area are also 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.

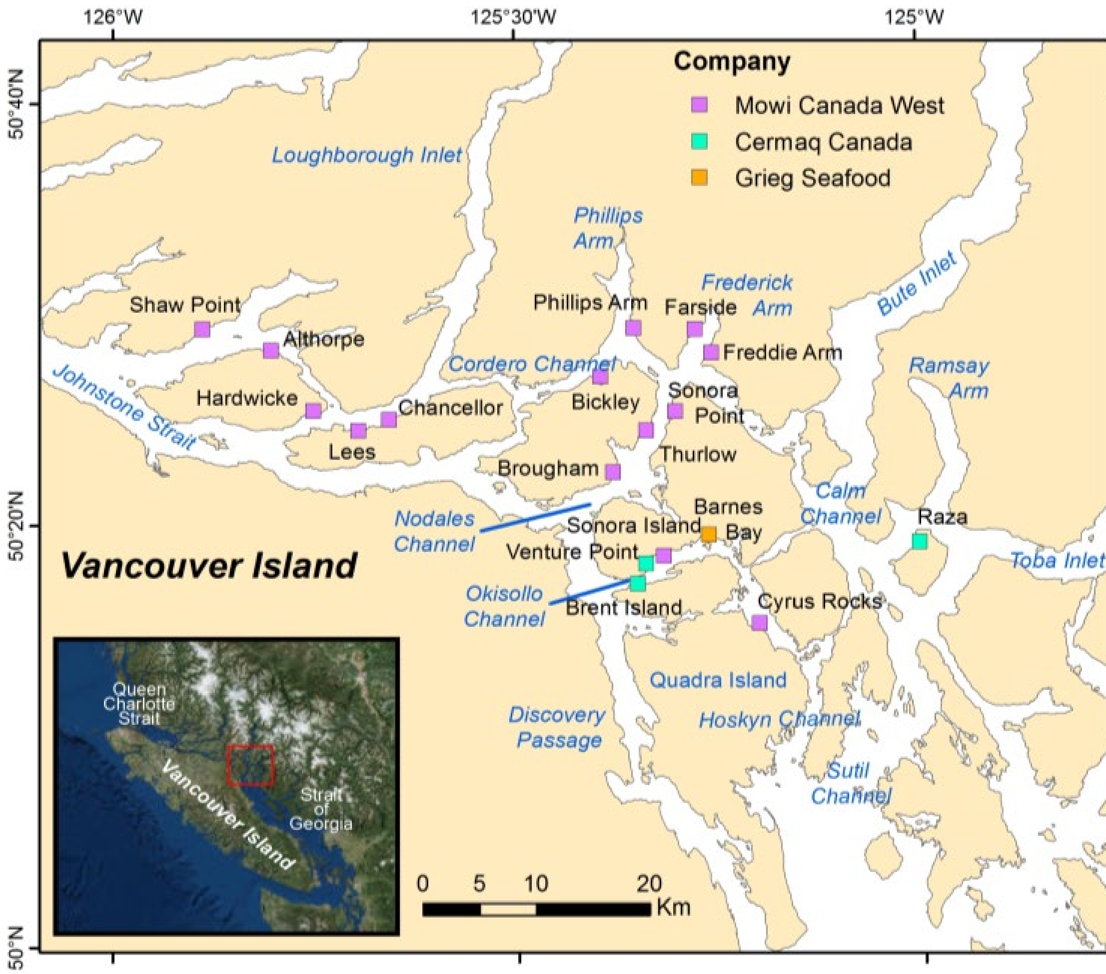

Figure 1. Locations of Atlantic Salmon farms in the Discovery Islands area (Fish Health Surveillance Zone 3-2 and three farms in Fish Health Surveillance Zone 3-3) included in this risk assessment. Symbol size for fish farms is not to scale. The insert illustrates the location of the Discovery Islands area in BC. 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 *R. salmoninarum* 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 *R. salmoninarum* infection attributable to Atlantic Salmon farms in the Discovery Islands area on the abundance and diversity of Fraser River Sockeye Salmon.

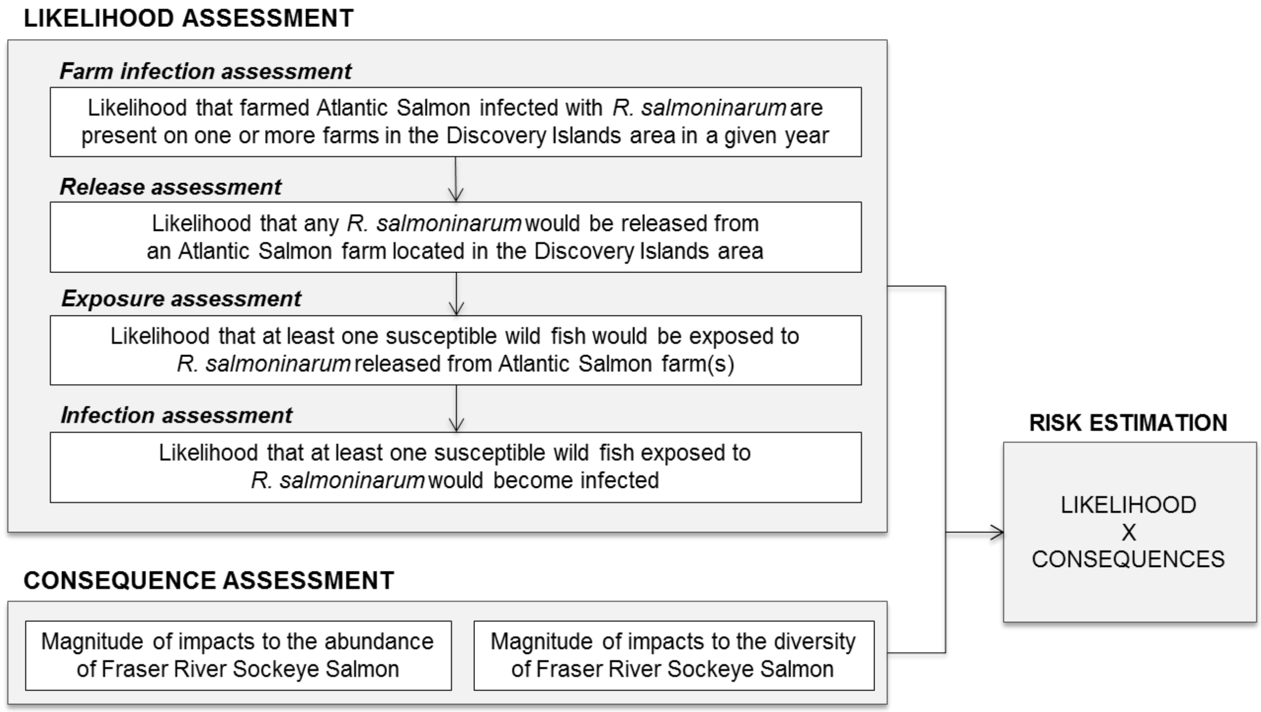

Figure 2. Conceptual model to assess the risks to Fraser River Sockeye Salmon resulting from Renibacterium salmoninarum *attributable to Atlantic Salmon farms located in the Discovery Islands area, British Columbia. Adapted from Mimeault et al. (2017).*

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.

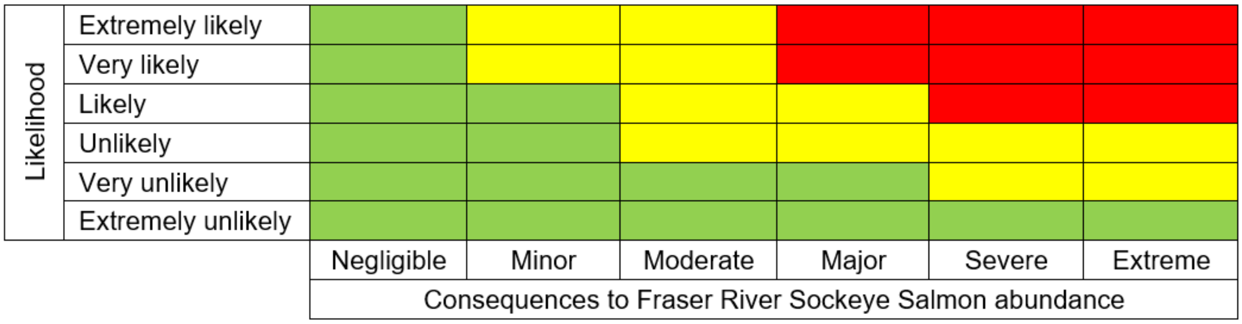

Figure 3. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon abundance. Green, yellow and red represent minimal, moderate and high risk, respectively.

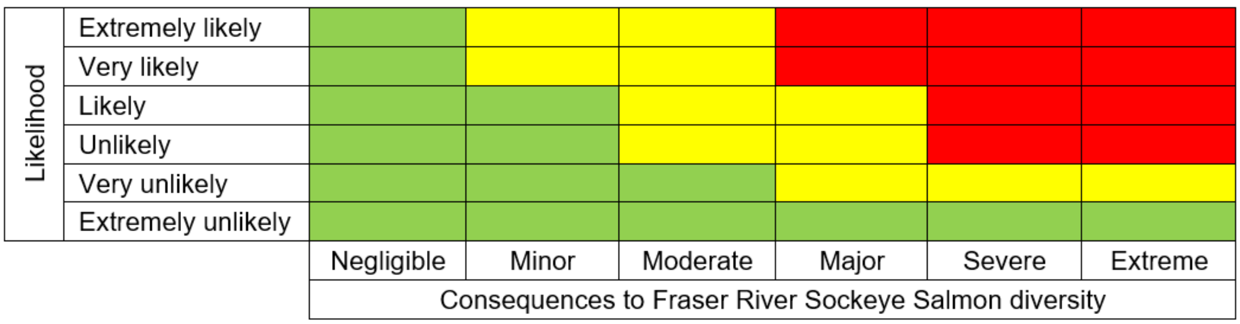

Figure 4. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon diversity. Green, yellow and red represent minimal, moderate and high risk, respectively.

3 LIKELIHOOD ASSESSMENT

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

3.1.2 Considerations

Factors contributing to the detection of *R. salmoninarum* 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, BKD is diagnosed in an Atlantic Salmon population when the population is undergoing treatment for the disease or if a substantial proportion of the fish sampled have gross lesions consistent with the disease, characteristic microscopic lesions with visualization of the agent in the lesions, and evidence from records to determine population level disease (I. Keith, DFO, pers. comm., 2018).

Rhodes and Mimeault (2019) summarized audit-based detections of *R. salmoninarum* and farm-level BKD 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:

- From 2002 to 2016, *R. salmoninarum* was detected during audits in all years except in 2010 and 2015;
- BKD and/or *Renibacterium*-like bacteria was diagnosed through histology in a small number of fish (n=1 to 20) in 12 years (2002 to 2009, 2011-2014 and 2016) on a total of 16 farms; and
- BKD was diagnosed at the farm-level in six years (2002, 2004-2007, 2009) on a total of six farms.

Although the DFO FHASP is not designed to capture incidence or prevalence, the above detections are indicative of the presence of the pathogen and/or disease in some individuals on farms. These data provide evidence that low levels of *R. salmoninarum* may be present in farmed populations that may only be detectable using sensitive diagnostic methods.

As part of a research project, molecular evidence of *R. salmoninarum* genomic DNA has been reported in audit samples collected between April 2011 and December 2013 on 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 fall of 2002 with the exception of 2013, 2014 and first three quarters of 2015 during which mortalities had to be reported by cause (Wade, 2017). During this time, FHEs were still reported to the BC Salmon Farmers Association (BCSFA) but were not required to be reported to DFO as a condition of licence. The BCSFA provided the FHEs that occurred on Atlantic Salmon farms in the Discovery Islands area during this period to inform this assessment.

A total of 10 FHEs attributed to BKD were reported on a total of seven 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 BKD, 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 *R. salmoninarum* infection on Atlantic Salmon farms.

CFIA grants permits for Aquatic Animal Domestic Movements to contain certain aquatic animal reportable diseases. As BKD is not a reportable disease for finfish in Canada (CFIA, 2018), 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 BKD. For every aquaculture related transfer application, fish health reports and husbandry records are examined by Aquaculture Management Division staff prior to transfer. If any clinical signs of diseases are seen, or there are any other concerns, the 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).

Diagnostic procedures for the detection of the bacterium and BKD differ among companies and are context dependent. In addition to routine health checks, companies also perform active and passive surveillance for *R. salmoninarum* and/or BKD during disease investigations and special projects. Observations of gross lesions indicative of BKD in fish during fish health visits can also be recorded. Based on farm history, clinical signs and macroscopic lesions in the fish kidney, a presumptive case of BKD can be identified by trained fish health staff, and confirmatory testing is not always pursued. Diagnostic tests include histology and tissue imprints, while enzyme-linked immunosorbent assay (ELISA) and molecular tests can be used both as confirmatory and screening tests and are done 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), *R. salmoninarum* prior to transfers from freshwater to seawater facilities, and for *P. 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). The use of vaccines in the prevention of BKD varies among companies. Renogen® is the only commercial BKD vaccine available for use in Canada.

Cermaq Canada used to vaccinate fish against BKD but since 2016, no longer does (B. Milligan, Cermaq Canada, pers. comm., 2018). Grieg Seafood does not systematically vaccinate fish against BKD but have been conducting trials with the vaccine to determine its potency to protect against salmonid rickettsial septicaemia (SRS) (P. Whittaker and T. Hewison, Grieg Seafood, pers. comm., 2018). Since 2015, Mowi Canada West has vaccinated 100% of their Atlantic Salmon with Renogen® prior to transfer to seawater to minimize prevalence and severity of BKD (D. Morrison, Mowi Canada West, pers. comm., 2018).

3.1.2.2.4 Treatment

Cermaq Canada, Grieg Seafood and Mowi Canada West may treat their fish with in-feed oxytetracycline (OTC) for 10 to 14 days if BKD or clinical signs of the disease are present in

Atlantic Salmon on marine production sites (B. Milligan, Cermaq Canada, pers. comm., 2018; P. Whittaker and T. Hewison, Grieg Seafood*,* pers. comm*.,* 2018; D. Morrison, Mowi Canada West, pers. comm., 2018). The length of the treatment is dependent on veterinarian judgement and size of the fish. A single treatment is often sufficient, however, in rare instances, more than one treatment may be required (D. Morrison, Mowi Canada West, pers. comm., 2018).

If clinical signs of BKD are observed in hatcheries, Cermaq Canada may treat fish with OTC and, depending on severity of infection or if treatment was determined to be ineffective, fish would be culled. Fish would only be transferred if diagnostic tests returned negative (D. New and B. Milligan, Cermaq Canada, pers. comm., 2018).

3.1.2.2.5 Egg disinfection in hatcheries

Egg disinfection following fertilization and water hardening is a requirement of the SHMP (DFO, 2015). Egg disinfection can be conducted either at the broodstock facility and/or at the hatchery (DFO, 2015).

Company-specific egg disinfection protocols are described in their proprietary SOPs accompanying the SHMP. Cermaq Canada conducts double egg disinfection (at source and at the hatchery) (B. Milligan, Cermaq Canada, pers. comm., 2018).

Egg disinfection is one of the fish health management practice to prevent BKD (reviewed in Rhodes and Mimeault (2019)). The immersion in iodine at 100 to 500 mg L^{-1} for 15 to 20 minutes can inactivate most bacteria, although the agglutinating nature of *R. salmoninarum* can shield many cells and allow them to survive (Bullock et al., 1978; Evelyn et al., 1984).

3.1.2.2.6 Broodstock screening

Disease screening at the time of spawning is a requirement of the SHMP to mitigate risk of vertical transmission of pathogens to progeny (DFO, 2015). Tests performed for broodstock screening are at the discretion of the company veterinarian. Cermaq Canada screens every female broodstock for *R. salmoninarum* by quantitative fluorescent antibody technique and by PCR since 2018. Eggs from positive females are discarded (D. New and B. Milligan, Cermaq Canada, pers. comm., 2018). Grieg Seafood does not have broodstock in BC (P. Whittaker and T. Hewison, Grieg Seafood, pers. comm., 2018). Mowi Canada West screens every female broodstock for *R. salmoninarum* by ELISA. All eggs from positive females are discarded (D. Morrison, Mowi Canada West, pers. comm., 2018).

R. salmoninarum can be transmitted from parent to progeny (Evelyn et al., 1984) hence the use of broodstock screening as a fish health management practice to prevent BKD (reviewed in Rhodes and Mimeault (2019)).

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, *R. salmoninarum* and/or BKD was detected in at least one fish in 19.8% of site visits with clinical examination and/or testing for the bacterium. Overall, macroscopic lesions of BKD or positive diagnostic test results for *R. salmoninarum* was found in at least one fish in each of 11 farms in 2011, five farms in 2012, three farms in 2013, two farms in 2014, 2015 and 2016, and four farms in 2017. Refer to Appendix C for more details.

3.1.2.4 Summary of *Renibacterium salmoninarum* and bacterial kidney disease on Atlantic Salmon farms in the Discovery Islands area

In this risk assessment, evidence of *R. salmoninarum* infection and/or BKD refers to fish sampled during routine screenings by the industry, regulatory programs, fish health events, and any other diagnostic workups on the farms with (i) positive laboratory test results targeting *R. salmoninarum* (ELISA, PCRs), (ii) indicative of *R. salmoninarum* and/or BKD (histology, tissue imprints), or (iii) clinical signs and gross lesions of BKD recognized by trained personal with or without confirmation by diagnostic testing.

Table 7 summarizes data related to Atlantic Salmon farms in the Discovery Islands area with evidence of *R. salmoninarum* infections and/or BKD signs and diagnoses by year between 2002 and 2017. Data were collated separately from regulatory reporting requirements (results from the FHASP; FHEs and mortality events reported by the industry to DFO) and from industry syndromic surveillance, 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 necessarily result in clinical signs or disease in a population. *Renibacterium salmoninarum* was detected or reported on at least one farm in all years between 2002 and 2017, resulted in farm-level BKD in six of 15 years and was attributed to FHEs in four of 15 years.

Overall, there is evidence of *R. salmoninarum* infection between 2002 and 2017 on 17 of the 18 active Atlantic Salmon farms in the Discovery Islands area. Farm-level BKD and FHEs attributed to BKD have been reported on a total of seven farms, all prior to 2011. Although there have been several detections since 2011, which would indicate that BKD may be common, the severity of infection is low as it has not resulted in a FHE since 2011. Mortality event data from 2011 to 2017 also show that no events have occurred (data prior to 2011 are not available).

Table 7. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of Renibacterium salmoninarum *infection and/or bacterial kidney disease (BKD) summarized by year. Data include results from industry observations by fish health staff and diagnostic testing (2011-2017), results from the Fish Health Audit and Surveillance Program (FHASP) (2002-2016), fish health events (FHEs) (2002-2017) and mortality events (2011-2017) reported by the industry to Fisheries and Oceans Canada (DFO). Results include detection in a single fish. NA: data not available. Months with evidence of* R. salmoninarum *and/or BKD are shaded and bolded.*

Year	Number of active farms	Industry data	FHASP data		Reported to DFO by industry	
		Number of farms with evidence of *R. salmoninarum* and/or BKD / total number of farms with examined fish	Number of farms with BKD and/or *Renibacterium*-like bacteria identified through histology / total number of farms audited	Number of farms with farm-level BKD diagnoses / total number of farms audited	Number of farms with FHEs attributed to BKD	Number of farms with mortality events attributed to BKD
2002	NA	NA	**2/3**	**1/3**	0	NA
2003	NA	NA	**1/4**	0/4	0	NA
2004	14	NA	**3/9**	**1/9**	0	NA
2005	15	NA	**3/11**	**3/11**	**5**	NA
2006	16	NA	**4/12**	**3/12**	0	NA
2007	16	NA	**1/13**	**1/13**	0	NA
2008	17	NA	**6/15**	0/15	**1**	NA
2009	18	NA	**4/14**	**2/14**	**1**	NA
2010	16	NA	0/4	0/4	**1**	NA
2011	17	**11/14**	0/8	0/8	0	0
2012	13	**5/8**	**4/12**	0/12	0	0
2013	8	**3/7**	**1/7**	0/7	0	0
2014	10	**2/7**	**2/8**	0/8	0	0
2015	10	**2/7**	0/9	0/9	0	0
2016	11	**2/11**	**1/11**	0/11	0	0
2017	12	**4/10**	NA	NA	0	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 a *R. salmoninarum* 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 Renibacterium salmoninarum *are present on one or more Atlantic Salmon farms in the Discovery Islands area under the current fish health management practices. BKD: bacterial kidney disease; FHE: fish health event; PCR: polymerase chain reaction; SHMP: salmonid health management plan.*

Contributing factors	Limiting factors

• Atlantic Salmon are susceptible to *R. salmoninarum* infections;
• Fish health audits:
  o BKD and/or *Renibacterium*-like bacteria were detected through histology on at least one farm in 12 years between 2002 and 2016; and
  o BKD was diagnosed at the farm level on at least one farm in six different years between 2002 and 2009;
• The industry reported FHEs attributed to BKD in 2005, 2008, 2009 and 2010;
• Overall, from 2002 to 2017, there is evidence of *R. salmoninarum* and/or BKD:
  o on a total of 17 Atlantic Salmon farms; and
  o on at least one farm every year between 2002 and 2017; and
• Vaccination to protect against BKD is voluntary; only one company systematically vaccinates fish against BKD.
	• All female broodstock are tested for *R. salmoninarum* and eggs from positive females are discarded, limiting the introduction of *R. salmoninarum* on Atlantic Salmon farms;
	• Hatchery-origin infection is mitigated through egg disinfection, a requirement of the SHMP;
	• Three farms conduct diagnostic testing for *R. salmoninarum* through PCR prior to live fish transfers from freshwater to seawater while other farms conduct histology prior to any live fish transfer that can detect active BKD or *R. salmoninarum*;
	• Since 2015, most farmed Atlantic Salmon reared in the Discovery Islands area (14 out of 18 farms) are vaccinated against BKD; and
	• SHMPs 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 *R. salmoninarum* are present on one or more Atlantic Salmon farms in the Discovery Islands area is **very likely** under the current farm practices given evidence of *R. salmoninarum* on farms in all years between 2002 and 2016. 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 *R. salmoninarum* are present, what is the likelihood that any *R. salmoninarum* 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 *R. salmoninarum* from infected fish; and fish health management practices.

3.2.2.1 Atlantic Salmon rearing method

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 *Renibacterium salmoninarum* from infected fish

Bacterial shedding rates from *R. salmoninarum*-infected or diseased Atlantic Salmon are unknown (Rhodes and Mimeault, 2019). Shedding rates from other species were used as proxy in this risk assessment. The only two studies (McKibben and Pascho, 1999; Purcell et al., 2016) reporting shedding of *R. salmoninarum* from infected fish are limited to Chinook Salmon (*O. tshawytscha*) in freshwater.

McKibben and Pascho (1999) challenged Chinook Salmon (27 g) by injection and reported *R. salmoninarum* concentrations in water at different times (5 to 30 days) post-injection from which Rhodes and Mimeault (2019) estimated shedding rates of 4.1×10^5 cells per fish per hour.

Purcell et al. (2016) challenged Chinook Salmon (5 g) with *R. salmoninarum* by injection and reported the highest mean shedding rate to be 2.1×10^5 cells per fish per hour. Calculated values for heavily infected fish based on a correlation between bacterial loads in the kidney and the quantity of shed bacteria reported by Purcell et al. (2016) estimate shedding rates of 6.5×10^6 and 3.1×10^6 cells per fish per hour at 8°C and 12°C, respectively (Rhodes and Mimeault, 2019).

Asymptomatic but infected salmon and trout have also been reported to shed bacteria (Balfry et al., 1996); however, shedding rates in subclinical fish have not been reported (Rhodes and Mimeault, 2019). The positive correlation between bacterial loads in the kidney and the quantity of shed bacteria at 8 and 12°C identified by Purcell et al. (2016) may suggest that subclinically infected, or asymptomatic fish, may shed at a lower rate (Rhodes and Mimeault, 2019). *Renibacterium salmoninarum* was detected by PCR in water from tanks containing asymptomatic Atlantic Salmon smolts (average weigh 80 g) (Griffiths et al., 1998).

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 by Fraser et al. (2006) to be effective against BKD.

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 *R. salmoninarum* are present on at least one farm; and
- Biosecurity measures are effective against *R. salmoninarum*.

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 Renibacterium salmoninarum *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
• Chinook Salmon showing clinical signs of BKD shed *R. salmoninarum* in both freshwater and marine environment (Balfry et al., 1996; McKibben and Pascho, 1999; Purcell et al., 2016); • Subclinically *R. salmoninarum*-infected Atlantic Salmon (Griffiths et al., 1998) and Chinook Salmon (Balfry et al., 1996) shed the bacteria in faeces; and • Atlantic Salmon in the Discovery Islands area are reared in net pens allowing pathogens, including *R. salmoninarum*, 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 *R. salmoninarum* 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, and Chinook Salmon as a proxy species, shed the bacterium. This conclusion was made with **high certainty** given abundant, robust and peer-reviewed evidence of shedding of *R. salmoninarum* from infected salmonids.

3.2.4.2 Release through vectors and fomites

It was concluded that the likelihood that *R. salmoninarum* 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 *R. salmoninarum* would be released from an Atlantic Salmon farm should it become infected.

3.3 EXPOSURE ASSESSMENT

3.3.1 Question

Assuming that *R. salmoninarum* 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 *R. salmoninarum* 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 *R. salmoninarum* in the marine environment; and timing of *R. salmoninarum* infections on Atlantic Salmon farms in the Discovery Islands area.

3.3.2.1 Susceptible species

Based on comparative studies of morbidity and mortality resulting from experiments in which salmonids were injected with *R. salmoninarum* in freshwater, Rhodes and Mimeault (2019) ranked susceptibility in three main categories: Sockeye, Chinook, and Chum (*O. keta*) salmon being the most susceptible species, Coho (*O. kisutch*) and Atlantic Salmon having an intermediate susceptibility and Lake (*Salvelinus namaycush*), Brown (*S. trutta*), Bull (*S. confluentus*) and Rainbow (*O. mykiss*) and steelhead trout (*O. mykiss*) as being less susceptible. Highlighting the caveat that these comparative studies were conducted through an exposure route that is not environmentally relevant, Rhodes and Mimeault (2019) nevertheless, report that these results have been corroborated with hatchery and field results.

In addition to Sockeye Salmon, other susceptible Pacific salmon species considered in this risk assessment are Chinook and Chum salmon as they are considered highly susceptible in freshwater (reviewed in Rhodes and Mimeault (2019)). Coho Salmon was also considered as Pacific salmon farmers in BC reported that Chinook and Coho salmon were affected the most by BKD (BC Centre for Aquatic Health Sciences, 2010). Pink Salmon *(O. gorbuscha)* were also considered as they are susceptible to infection with *R. salmoninarum* and BKD (Bell, 1961; Banner et al., 1986; Kent et al., 1998).

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 area from mid-May to mid-July, with peak catches in early-to-mid June.

Out of the 16 years with evidence of *R. salmoninarum* and/or BKD on Atlantic Salmon farms since 2002, 11 years reported evidence 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 16 years with evidence of *R. salmoninarum* and/or BKD on Atlantic Salmon farms since 2002; 13 years included evidence between June and October (Table 10 and Table 11).

3.3.2.4 Other Pacific salmon species in the Discovery Islands area

This section summarizes 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 Salmon were less abundant while Sockeye Salmon and steelhead trout (*O. mykiss*) were uncommon (Levings and Kotyk, 1983). Only two Sockeye Salmon were caught in this survey. Based on the 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.

Echo sounders 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 signals from Pacific salmon were high 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 were present 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 2,544.2 ± 3,177.0) and Pink (7.4 ± 10.7 to 1,416.7 ± 1,665.6) 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 other susceptible Pacific salmon species (Chinook, Chum, Coho and/or Pink salmon) and evidence of *R. salmoninarum* on Atlantic Salmon farms in the Discovery Islands area (Table 10 and Table 11).

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[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 *Renibacterium salmoninarum* survival in the marine environment

Rhodes and Mimeault (2019) reviewed the state of knowledge about the survival of *R. salmoninarum* in the environment. Studies most relevant to survival in the marine environment are reported here.

The survival of *R. salmoninarum* in the marine environment varies and depends on temperature, nutrient availability and initial concentration (Balfry et al., 1996). *Renibacterium salmoninarum* has been reported to survive in raw seawater for seven days at 10°C (Balfry et al., 1996). Viability was reduced to approximately 40% by eight hours and approximately to 1% by 24 hours and remained above 1% to seven days (Balfry et al., 1996).

Given its agglutinating nature (Daly and Stevenson, 1987; Bruno, 1988; Daly and Stevenson, 1989), *R. salmoninarum* most likely exists in the environment primarily in a particulate-associated form, and its hydrodynamics may be better modelled as larger particles (e.g., 5-50 µm) rather than as very tiny (i.e., < 1 µm) planktonic bodies (Rhodes and Mimeault, 2019).

3.3.2.6 Timing of *Renibacterium salmoninarum* and BKD on Atlantic Salmon farms in Discovery Islands area

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

- based on industry surveillance and screening results, *R. salmoninarum w*as confirmed on farms in all months of the year either by histology, tissue imprints, ELISA, PCR or clinical examination;
- based on FHASP results, *R. salmoninarum* infections and/or BKD were reported in all months of the year while BKD farm-level diagnoses were reported in all months except March, November and December;
- FHEs were attributed to BKD in the months of February to June and October; and
- no mortality events (2011-2017) were attributed to BKD.

Overall, based on all sources of data between 2002 and 2017, *R. salmoninarum* was reported on at least one Atlantic Salmon farm in the Discovery Islands area in all months of the year. No seasonal patterns of infection or disease could be found. Table 11 summarizes evidence from all sources per year and month.

Table 10. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of Renibacterium salmoninarum *and/or bacterial kidney disease (BKD) 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 observations by fish health staff and diagnostic testing (2011-2017), results from the Fish Health Audit and Surveillance Program (FHSAP) (2002-2016), fish health events (FHEs) (2002-2017) and mortality events (2011-2017) reported by the industry to Fisheries and Oceans Canada (DFO). Results include detection in a single fish. Letters represent months from January to December. Months with wild fish in the Discovery Islands area are shaded and months with evidence of* R. salmoninarum *and/or BKD 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	CS	CS	X	X	X	X	X	X	X	X	CS	CS
Evidence of *R. salmoninarum* and/or BKD	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Number of farms with evidence of *R. salmoninarum* and/or BKD / total number of farms with fish health visits and testing	**5/10**	**4/11**	**5/13**	**3/10**	**7/14**	**6/16**	**3/10**	**6/12**	**1/11**	**3/11**	**2/11**	**1/10**
Number of farms with BKD and *Renibacterium*-like bacteria identified through histology / total number of farms audited (FHASP data)	**6/14**	**3/11**	**1/5**	**5/14**	**4/10**	**1/10**	**6/12**	**3/14**	**3/11**	**2/16**	**2/13**	**1/10**
Number of farms with farm-level BKD diagnoses / total number of farms audited (FHASP data)	**2/14**	**2/11**	0/5	**1/14**	**3/10**	**1/10**	**1/12**	**1/14**	**1/11**	**1/16**	0/13	0/10
Number of farms with FHEs attributed to BKD (reported by industry)	0	**1**	**1**	**5**	**1**	**1**	0	0	0	**1**	0	0
Number of farms with mortality events attributed to BKD (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 Renibacterium salmoninarum *and/or bacterial kidney disease (BKD) 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* R. salmoninarum *and/or BKD 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	**1**	**1**	0
2003	0	**1**	0	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	**1**	**2**	0	0	0	0
2005	0	**1**	**1**	**3**	**2**	**2**	**1**	0	0	0	0	0
2006	**1**	0	0	0	**2**	0	0	0	**2**	0	**1**	0
2007	0	**1**	0	0	0	0	0	0	0	0	0	0
2008	**1**	**1**	0	**4**	0	0	**1**	0	**1**	0	0	**1**
2009	**2**	0	**1**	**2**	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0	0	**1**	0	0
2011	**2**	**3**	**2**	**1**	**3**	**1**	0	**3**	0	**2**	0	0
2012	**1**	0	0	**2**	**4**	**3**	**2**	**2**	0	**2**	0	0
2013	**2**	0	**2**	0	**2**	0	**1**	0	**1**	0	0	0
2014	0	**1**	0	**1**	0	**1**	**2**	**1**	0	0	**1**	0
2015	0	0	0	0	**2**	**1**	0	0	0	0	0	0
2016	0	0	0	0	0	**1**	0	**1**	0	0	**1**	0
2017	**2**	0	**1**	**1**	**3**	0	0	**1**	0	**1**	0	**1**

3.3.3 Assumptions

- *Renibacterium salmoninarum* has been released from at least one Atlantic Salmon farm operating in the Discovery Islands area;
- Positive detection of *R. salmoninarum* is evidence that the pathogen is present in sampled fish; *R. salmoninarum*-infected fish are shedding the bacterium;
- Evidence of shedding is limited to months with evidence of infection or disease on farms;
- Sockeye 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 to be exposed to *R. salmoninarum* 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 susceptible Pacific salmon species would be exposed to Renibacterium salmoninarum *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)); • There is temporal overlap between Fraser River Sockeye Salmon and other susceptible Pacific salmon species and evidence of *R. salmoninarum* on Atlantic Salmon farms in the Discovery Islands area; and *R. salmoninarum* can survive up to one week in 10°C seawater under laboratory conditions (Balfry et al., 1996); and • The prevalence of BKD in Atlantic Salmon on BC farms was estimated to be around 3% in BC (BC Centre for Aquatic Health Sciences, 2010) (see section 3.4.2.4).	• 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); • Analysis of Scottish BKD outbreaks did not identify hydrographic spread as a main risk pathway for *R. salmoninarum* but is still a possibility in the marine environment over a short distance (Murray et al., 2011); and • Although faeces are considered a significant source of shed *R. salmoninarum* (Balfry et al., 1996), large particles would sink and settle to the bottom hence reducing potential exposure to the bacterium released from infected farms.

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

The likelihood that at least one susceptible fish could be exposed to *R. salmoninarum* attributable to Atlantic Salmon farms was informed by the number of years with evidence of *R. salmoninarum* and/or BKD during periods of time when susceptible fish are present in the area, divided by the number of years with evidence of *R. salmoninarum* and/or BKD (16 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 *R. salmoninarum* attributable to Atlantic Salmon farms located in the Discovery Islands area through waterborne exposure is **very likely** under the current fish health management practices given their temporal overlap in the Discovery Islands area with reports of *R. salmoninarum* on farms. Out of the 16 years with evidence of *R. salmoninarum* and/or BKD on farms since 2002, 11 years had evidence between May and July which corresponds to when juvenile Fraser River Sockeye Salmon are expected to be present in the 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 *R. salmoninarum* and BKD 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 *R. salmoninarum* attributable to an Atlantic Salmon farm located in the Discovery Islands area through waterborne exposure is **very likely** under the current fish health management practices given the temporal overlap in the Discovery Islands area with reports of *R. salmoninarum* on farms. Out of the 16 years in which evidence of *R. salmoninarum* and/or BKD has been recorded on farms, 13 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 (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 *R. salmoninarum* and BKD 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 that at least one other susceptible Pacific salmon species could be exposed to *R. salmoninarum* 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 area at any time of the year. This conclusion was made with **reasonable uncertainty** given the lack of data to support presence of all other susceptible species in the Discovery Islands area at any time of the year but robust and abundant data about the occurrence of *R. salmoninarum* and BKD on Atlantic Salmon farms.

3.4 INFECTION ASSESSMENT

3.4.1 Question

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

3.4.2 Considerations

Considerations include oceanographic and environmental conditions; minimum infectious and lethal doses; estimated duration of exposure; estimated infection pressure from farms; hydrodynamic dispersal; and vaccine efficacy.

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 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).

Data about *R. salmoninarum* survival in the environment is scarce. Balfry et al. (1996) reported that the bacterium survived up to 7 days in raw seawater (10ºC and 22‰) with viability reduced to approximately 40% in eight hours, 1% in 24 hours, and remained approximately at 1% for seven days.

3.4.2.2 Minimum infectious and lethal doses

The minimum dose of *R. salmoninarum* necessary to cause infection or mortality in Sockeye Salmon has not been determined (reviewed in Rhodes and Mimeault (2019)). In absence of such data, results from immersion studies conducted in other salmonids were used as proxy data in this risk assessment.

The lowest dose of *R. salmoninarum* that caused infection was reported in Chinook Salmon (weight not available) in freshwater when exposed to 7×10^2 *R. salmoninarum* cells/mL (7×10^8 cells/m^3) for 24 hours (Elliott and Pascho (1995) as cited in McKibben and Pascho (1999)). The infection was demonstrated by detection of *R. salmoninarum* by BKD-ELISA in fish tissue 100 days after exposure.

The lowest dose of *R. salmoninarum* that caused mortalities was reported in Chinook Salmon (48.9 ± 0.5 g) immersed for 15 minutes in freshwater containing 3×10^4 *R. salmoninarum* cells/mL (3×10^{10} cells/m^3) which resulted in 5% mortality 180 days after challenge (Murray et al., 1992).

The lowest infectious dose of 700 cells/mL for 24 hours and the lowest lethal dose of 3×10^4 cells/mL for 15 minutes can serve as proxy for the minimum infectious and lethal doses, respectively, with the caveat that these are freshwater exposure in Chinook Salmon (Rhodes and Mimeault, 2019).

3.4.2.3 Estimated duration of exposure

The potential duration that a susceptible fish species would be exposed to *R. salmoninarum* 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 *R. salmoninarum* infections and BKD 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 distance. 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 a short duration of exposure to fallowed farms (Rechisky et al., 2018).

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

3.4.2.3.2 *Duration of* Renibacterium salmoninarum *infection and bacterial kidney disease on Atlantic Salmon farms in the Discovery Islands area*

Given the regular occurrence of *R. salmoninarum* and BKD on Atlantic Salmon farms (Table 7, Table 10 and Table 11), a 1 to 3% estimated prevalence of BKD on marine Atlantic Salmon farms in BC based on expert opinion (see next section) (BC Centre for Aquatic Health Sciences, 2010), and evidence of shedding in subclinically infected salmon (Balfry et al., 1996), it is reasonable to assume that at any time, there could be low level shedding from an active Atlantic Salmon farm in the Discovery Islands area. Duration of treatment for BKD on Atlantic Salmon farms varies between 10 to 14 days.

3.4.2.4 Estimated *Renibacterium salmoninarum* infection pressure from Atlantic Salmon farms

There are no studies estimating the waterborne concentration of *R. salmoninarum* during a BKD outbreak on an Atlantic Salmon farm. Attempts to isolate and quantify *R. salmoninarum* from water samples from within a net-pen containing 14,000 Chinook Salmon that were experiencing high BKD-related mortalities (80% cumulative mortality) could only be obtained from one meter depth samples during feeding (Balfry et al., 1996). The estimated concentration in the triplicate plates was inconsistent (255 with a standard error of ± 179 cells/mL ($2.55 \times 10^8 \pm 1.79 \times 10^8$ cells/m^3). The reason for the lack of successful culturing of *R. salmoninarum* at other depths was attributed to the presence of faster growing seawater microflora (Balfry et al., 1996). Therefore, for the purpose of estimating the *R. salmoninarum* infection pressure from Atlantic Salmon farms, the waterborne concentration of the bacterium was estimated using 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 *R. salmoninarum* on an infected Atlantic Salmon farm is difficult to determine given that samples are 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 entire population.

The only estimate for BKD prevalence on Atlantic Salmon farms in BC is based on an evaluation of BKD impacts on the Canadian salmon aquaculture industry (BC Centre for Aquatic Health Sciences, 2010). As part of this evaluation, a questionnaire was developed to gather information related to prevalence, environmental practices, husbandry practices, and costs associated with the disease. The questionnaire was answered by fish health professionals representing commercial and enhancement interests in Canada. Respondents were asked to report the prevalence (0%, 1-3%, 3-5% or > 5% of population) of BKD among fish over the last generation and if there had been changes in the prevalence of BKD over the last five and 10 years.

Based on three respondents representing commercial Atlantic Salmon operations in BC, BKD was reported to have a 1 to 3% prevalence in Atlantic Salmon in the marine environment in BC (BC Centre for Aquatic Health Sciences, 2010). This prevalence was considered as expert opinion and used to estimate potential maximum waterborne concentration of *R. salmoninarum* on Atlantic Salmon farms in this risk assessment.

The maximum *R. salmoninarum* waterborne concentration over 24 hours was estimated based on the reported BKD prevalence on farms, bacterial shedding rates and farm volume which can be represented as follow:

$$[R. salmoninarum] = \frac{BKD\ prevalence\ on\ farms\ x\ \ Shedding\ rate\ x\ Time\ period}{Volume\ of\ farm\ net\ pens}$$

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 3% BKD prevalence on Atlantic Salmon farms (BC Centre for Aquatic Health Sciences, 2010) and a shedding rate of 6.5×10^6 cells *R. salmoninarum* per fish per hour (Rhodes and Mimeault (2019) based on McKibben and Pascho (1999)) (see section 3.2.2.2), the waterborne concentration after 24 hours of constant shedding was estimated to be 1.2×10^7 cells/m^3. This is considered to be an overestimate representing a worst-case scenario as it does not account for bacterial decay and hydrodynamic dispersion. Applying a calculated decay rate of 2.3 per day for *R. salmoninarum* in seawater (Rhodes and Mimeault, 2019), the waterborne *R. salmoninarum* concentration over 30 consecutive days would reach a maximum of 5.6×10^6 cells/m^3 on an average size farm (Figure 5). This estimate does not account for subclinically infected fish but is still considered to be an overestimate for several reasons:

1. BKD prevalence on farm (3%) is based on the highest prevalence available for Atlantic Salmon in BC;
2. the shedding rates (6.5×10^6 cells *R. salmoninarum* per fish per hour) were calculated based on heavily infected fish;
3. hydrodynamic dispersion of shed bacteria is not accounted for, therefore particles are assumed to stay within the farm; and
4. *R. salmoninarum* is an agglutinating bacterium which readily attaches to hard surfaces and particles, as such a portion would be removed from the water column.

The estimated waterborne *R. salmoninarum* concentration attributable to Atlantic Salmon farms would ideally be compared to the minimum dose required to infect Sockeye Salmon. In absence of such data, results from immersion studies conducted in other salmonids were used as proxy data in this risk assessment (reviewed in Rhodes and Mimeault (2019)).

To date, the lowest (but not necessarily minimum) reported dose to infect salmonids is 700 cells mL^{-1} (7.0×10^8 cells/m^3) following a 24-hour exposure (Elliott and Pascho, 1995) and the lowest (but not necessarily minimum) dose reported to have caused mortality is 3×10^4 cells mL^{-1} (3.0×10^{10} cells/m^3) following a 15-minute exposure (Murray et al., 1992) in Chinook Salmon juveniles in freshwater. These infectious and lethal doses determined in a proxy species in freshwater are approximately two to four orders of magnitude higher than the estimated *R. salmoninarum* concentrations on Atlantic Salmon farms (Figure 5). Sockeye and Chinook salmon are considered highly susceptible to *R. salmoninarum* infection, whereas Atlantic Salmon are considered to have an intermediate susceptibility (Rhodes and Mimeault, 2019).

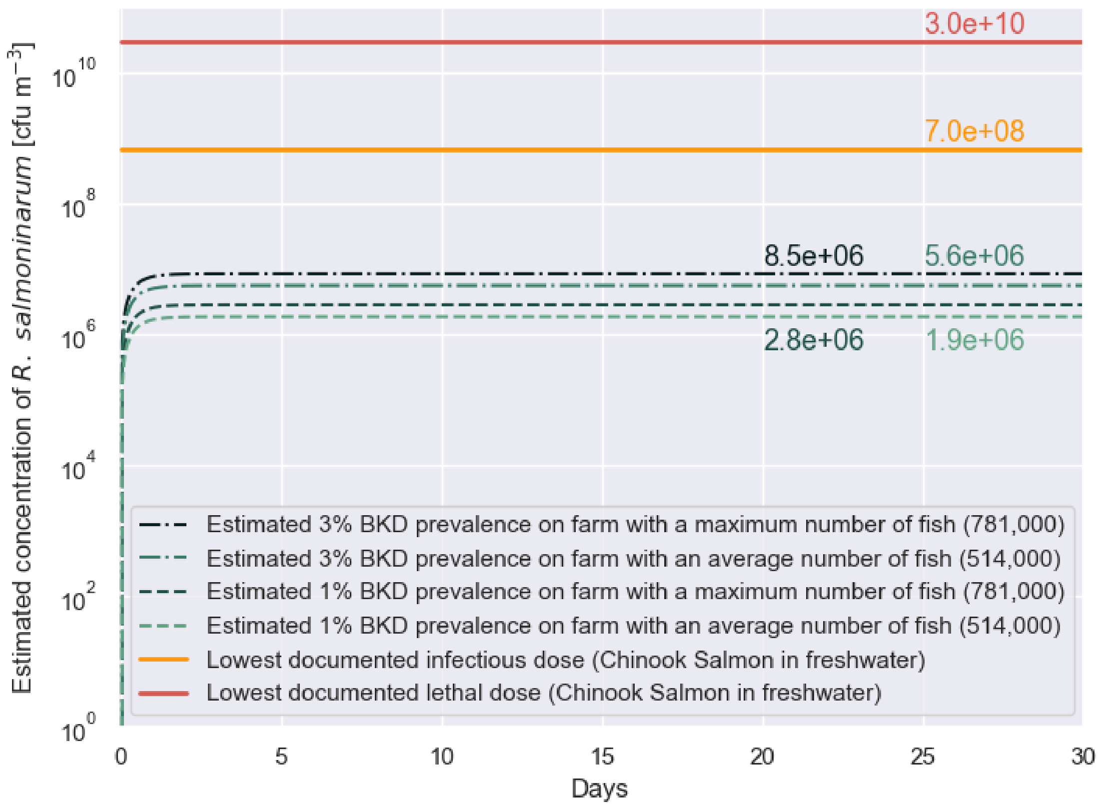

Figure 5. Estimated maximum waterborne concentration (cfu/m^3) for Renibacterium salmoninarum *on an infected Atlantic Salmon farm in the Discovery Islands area, BC. The green lines represent estimated waterborne concentrations assuming 514,000 or 781,000 fish on farm, a volume of 195,000 m^3, constant shedding from an estimated 1 to 3% BKD prevalence based on fish health professional survey, shedding rates (6.5 x 10^6 cells per fish per hour) estimated from highly infected juvenile Chinook Salmon, an estimated decay rate of 2.3 per day and no hydrodynamic dispersal. Under the above assumptions, waterborne concentration plateaus between 1.9 x 10^6 and 8.5 x 10^6 cells/m^3.*

3.4.2.5 Hydrodynamic dispersal

In a study of BKD outbreaks in farmed Atlantic Salmon in Scotland, hydrodynamic transmission of *R. salmoninarum* in seawater was found to be greatly increased when the bacteria are bound to particles (Murray et al., 2011). Modelled results indicate transportation over many kilometers with two to three orders of magnitude reduction in concentration (Murray et al., 2011).

The same study did not identify hydrographic spread as a main risk pathway for *R. salmoninarum* but concluded that in that outbreak, it is still a possibility over a short distance (Murray et al., 2011). They concluded that any hydrodynamic transmission is likely to be localized given that *R. salmoninarum* does not survive long in water (Murray et al., 2012).

Modeling of hydrodynamic dispersal of *R. salmoninarum* released from Atlantic Salmon farms in the Discovery Islands area was not conducted given that the estimated maximum waterborne concentration on *R. salmoninarum*-infected Atlantic Salmon farms was approximately two orders of magnitude lower than concentrations reported to be infectious in Chinook Salmon, a species considered more susceptible than Atlantic Salmon.

3.4.2.6 Vaccine efficacy

Data to estimate the efficacy of the Renogen® vaccine are limited to one laboratory study conducted in freshwater with Atlantic Salmon. This study suggests a vaccine efficacy of 72 to 91% (Salonius et al., 2005).

3.4.3 Assumptions

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

3.4.4 Likelihood of infection

Table 13 presents the main factors contributing to and limiting the likelihood that a susceptible salmonid species would become infected with *R. salmoninarum* 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 13. Factors contributing to and limiting the likelihood that Fraser River Sockeye Salmon and other susceptible Pacific salmon species would become infected with Renibacterium salmoninarum *released from infected Atlantic Salmon farms in the Discovery Islands area under current fish health management practices. BKD: bacterial kidney disease.*

Contributing factors	Limiting factors
• Sockeye, Chinook, Chum, Coho and Pink salmon are susceptible to BKD; • Water temperature and salinity in the vicinity of Atlantic Salmon farms are suitable for *R. salmoninarum* survival; • 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 *R. salmoninarum* waterborne concentrations in farm net pens (5.6×10^6 cells/m^3 on average size farm) is approximately $1/125^{th}$ of the 24-hr infectious concentration (7×10^8 cells/m^3) in Chinook Salmon, which is the lowest infectious dose reported in Pacific salmon; • Based on a telemetry study, juvenile Sockeye Salmon spend limited time (minutes) in the vicinity of fallowed farms (Rechisky et al., 2018); and • Since 2015, most farmed Atlantic Salmon reared in the Discovery Islands area (14 out of 18 farms) are vaccinated against BKD.

The likelihood of infection was considered separately for the three exposure groups and resulted in the same conclusion. In absence of data for Sockeye, Chum, Coho or Pink salmon, studies conducted with Chinook Salmon were used as proxy.

It was concluded that the likelihood of at least one Fraser River Sockeye Salmon or other susceptible Pacific salmon species to become infected with *R. salmoninarum* attributable to

Atlantic Salmon farms in the Discovery Islands area through waterborne exposure under the current fish health management practices is **extremely unlikely** given that the estimated waterborne concentration of *R. salmoninarum* on Atlantic Salmon farms is approximately 1/125th of the lowest concentration reported to cause infection in Chinook Salmon. This conclusion was made with **reasonable uncertainty** given incomplete data and reliance on surrogate data about shedding rates, infectious doses and lethal doses.

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 14 summarizes the likelihood assessment. It was concluded that the likelihood that wild susceptible fish would become infected with *R. salmoninarum* released from Atlantic Salmon farms in the Discovery Islands area is **extremely unlikely** for all exposure groups.

Table 14. Summary of the likelihood and uncertainty rankings in the Renibacterium salmoninarum *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">Very likely
(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 assessments</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">Very likely
(reasonable certainty)</td><td colspan="2">Very likely
(reasonable certainty)</td><td colspan="2">Extremely likely
(reasonable uncertainty)</td></tr>
<tr><td>Likelihood of infection</td><td colspan="2">Extremely unlikely
(reasonable uncertainty)</td><td colspan="2">Extremely unlikely
(reasonable uncertainty)</td><td colspan="2">Extremely unlikely
(reasonable uncertainty)</td></tr>
<tr><td colspan="2">Combined exposure and infection likelihoods for each exposure group</td><td colspan="2">Extremely unlikely</td><td colspan="2">Extremely unlikely</td><td colspan="2">Extremely unlikely</td></tr>
<tr><td colspan="2">Combined likelihoods (farm infection, release, exposure and infection) for each exposure group</td><td colspan="2">Extremely unlikely</td><td colspan="2">Extremely unlikely</td><td colspan="2">Extremely unlikely</td></tr>
</table>

4 CONSEQUENCE ASSESSMENT

The consequence assessment aims to determine the potential magnitude of impact of *R. salmoninarum* attributed 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 very likely that Atlantic Salmon infected with *R. salmoninarum* would be present on at least one farm in the Discovery Islands area. The exposure assessment determined that infected fish have been present on up to four farms in any given month (see Table 11) and the infection assessment determined that it is extremely unlikely that susceptible Pacific salmon species would get infected as the estimated waterborne concentration of *R. salmoninarum* on Atlantic Salmon farms is approximately 1/125th of the lowest dose reported to cause infection in Chinook Salmon. Overall, the likelihood assessment concluded that it is extremely unlikely for susceptible Pacific salmon species to become infected with *R. salmoninarum* 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 *R. salmoninarum* attributable to those farms, the consequence assessment explores the potential magnitude of impacts to the number of returning adults and diversity of Fraser River Sockeye Salmon.

4.1 QUESTION

Assuming that at least one susceptible wild fish has been infected with *R. salmoninarum* 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; prevalence and impact in wild fish populations; BKD mortality in wild Sockeye Salmon; subclinical infections; estimates of Fraser River Sockeye Salmon density; proportion of Fraser River Sockeye Salmon potentially exposed to infected farms; and exposure over two generations.

4.2.1 *Renibacterium salmoninarum* infection dynamics

For a disease outbreak to occur, a combination of conditions that are unfavourable to the host (i.e., environmental and physiological) and favourable to the pathogen (i.e., presence of susceptible hosts, pathogen survival) are required.

R. salmoninarum is both horizontally (Murray et al., 1992) and vertically (Evelyn et al., 1984; Evelyn et al., 1986) transmitted. For juvenile Chinook Salmon in Puget Sound, there is evidence of density-dependent horizontal transmission in free-ranging populations in the first six-months after entering seawater (see Rhodes and Mimeault (2019)).

Following transmission of the bacterium, an incubation period of 80 days resulted in cumulative mortalities of approximately 2.5% under experimental conditions (Murray et al., 1992). While these data are from freshwater immersion challenges in Chinook Salmon, there are no salt water immersion challenge studies to draw on.

4.2.2 Prevalence of infection in wild Pacific salmonid populations

Information about the prevalence and impact of *R. salmoninarum* infections and diseases in wild fish population is scarce and highly variable.

Juvenile Chinook Salmon collected by DFO's Canadian Program on High Seas Salmon from the west coast of Vancouver Island to Southeast Alaska from 2002 through 2007 included approximately 5% of 334 fish with heavy infection (ELISA, OD > 1.00) with *R. salmoninarum* (Nance et al., 2010).

Marine-phase juvenile Fraser River Sockeye Salmon (1,530 fish from 45 stocks) collected from the Strait of Georgia from 2010-2012 exhibited a 0% infection prevalence for *R. salmoninarum* (screened through PCR) (Mahony et al., 2017). The authors, however, acknowledged that this finding contrasts with some DFO unpublished data in their discussion suggesting a widespread occurrence of *R. salmoninarum* in spawning Fraser River Sockeye Salmon with *R. salmoninarum* prevalence ranging from 1 to 89% depending on the year and stock (Mahony et al., 2017). *Renibacterium salmoninarum* has also been detected in female Sockeye Salmon in spawning condition screened as part of the DFO Salmonid Enhancement Program in BC (Rhodes and Mimeault, 2019).

Examination of 3,680 fish representing seven species of salmonids (Chinook Salmon, Chum Salmon, Coho Salmon, Pink Salmon, Sockeye Salmon, steelhead trout, Cutthroat Trout (*O. clarkii*)) collected offshore of Oregon and Washington found less than 4% infection in all species except Chinook Salmon, which had an infection prevalence of 11% (Banner et al., 1986). Only Chinook Salmon (2.8%) and Coho Salmon (0.3%) displayed overt signs of BKD.

4.2.3 Bacterial kidney disease mortality in wild Sockeye Salmon

Given the lack of information about the impacts of a *R. salmoninarum* infection and BKD in wild salmon populations (reviewed in Rhodes and Mimeault (2019)), on-farm mortality rates in Atlantic Salmon in BC were used as proxy data in this risk assessment. BKD often establishes as a chronic disease, causing continuous mortalities throughout the life cycle but especially after the first year and as fish reach market size (BC Centre for Aquatic Health Sciences, 2010).

It is reasonable to assume that Sockeye Salmon are exposed to *R. salmoninarum* attributable to farms for shorter durations and at lower concentrations than farmed Atlantic Salmon are during a FHE. Consequently, it is therefore reasonable to assume that Sockeye Salmon would, at worst, have disease outcomes (i.e., mortality) no more severe than unvaccinated farmed Atlantic Salmon. This is acknowledging that Fraser River Sockeye Salmon have additional sources of stress including, migrating, avoiding predators, and competing for resources. These factors, however, cannot be addressed given our current state of knowledge.

The aquaculture industry provided numbers of daily mortality and cause of death before, during and after FHEs attributable to BKD on Atlantic Salmon farms in the Discovery Islands area. A total of 10 FHEs were attributed to BKD since 2002 (Appendix B). Data were not available for FHEs reported before 2008. Data were obtained for the last four FHEs which occurred between 2008 and 2010 on three farms. During this time period, mortalities due to disease were not always recorded in a specific disease-related category. Consequently, when necessary, all mortalities reported in the silver, old, culled moribund, and disease categories were attributed to BKD. The following analysis of BKD mortalities as determined from these data (2008-2019) are therefore considered to be overestimates.

The 21-day rolling average of mortalities attributed to BKD at the farm level during the four FHEs remained under 0.04% in unvaccinated Atlantic Salmon, and even under 0.01% on some farms. Although most-to-all net pens were treated during those FHEs, the maximum 21-day rolling average for BKD-attributed mortality remained below 0.02% in most (83%) net pens. Mortalities were slightly elevated (reaching a maximum of 0.04% over 21 days) over a period of one to two months and decreased over four to six weeks after treatment. All farms on which a FHE attributed to BKD has been reported between 2008 and 2010 were treated with antibiotics.

Time between seawater stocking and the onset of the above FHEs ranged from nine to 17 months (mean of 12.5) while the FHEs reported in 2005 occurred from zero to six months after transfer (mortality data not available).

Despite being able to regularly detect BKD on marine sites in this area, there is no evidence of increases in mortality at the population level due to BKD on Atlantic Salmon farms in the Discovery Islands area between 2011 and 2017 (there were no audit-based farm-level diagnoses, no FHEs and no mortality events related to BKD). Additionally, although details about FHEs attributed to BKD on salmon farms located in other Fish Health Surveillance Zones of BC are not available, to date, there were no mortality event attributed to BKD on a salmon farm in BC, so it is reasonable to conclude that mortality attributable to BKD has never reached 2% in a day or 5% within a five-day period on BC salmon farms.

4.2.4 Subclinical infections with *Renibacterium salmoninarum*

Rhodes and Mimeault (2019) reviewed the state of knowledge for asymptomatic and subclinical infections with *R. salmoninarum*. Subclinical infections can occur during early stages of an acute infection before host responses have developed or can result from suboptimal conditions for acute disease development. Subclinical infections can persist through the lifecycle of the fish, through spawning and transfer to progeny (Rhodes and Mimeault, 2019).

Rhodes and Mimeault (2019) concluded that it is likely that there is some degree of immunosuppression in fish with subclinical disease. However, the consequences at the population level resulting from subclinical infections are unknown.

4.2.5 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.

4.2.5.1 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.

4.2.5.2 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 x 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 x 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 (400–2,000 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.

4.2.6 Estimates of the proportion potentially exposed to infected farms

This section estimates the proportion of Fraser River Sockeye Salmon population in the Discovery Islands area at the same time as *R. salmoninarum* infections and/or BKD are 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 during periods when *R. salmoninarum* infections and/or BKD 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 *R. salmoninarum* 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.

4.2.6.1 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 *R. salmoninarum* 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 infection(s). 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 these 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 8 and 100% (median=62% and mean=57%) of juveniles would have had the opportunity to be exposed to *R. salmoninarum* attributable to Atlantic Salmon farm(s) in the Discovery Islands area during their out-migration (Appendix D). 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).

4.2.6.2 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 D), 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 D) and only considering years with infections, between 0 and 89% (median=14% and mean=26%) of adults would have had the opportunity to be exposed *R. salmoninarum* attributable to Atlantic Salmon farm(s) in the Discovery Islands area during their returning migration (Appendix D). 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).

4.2.7 Estimates of exposure over two generations

The potential exposure of Fraser River Sockeye Salmon populations to Atlantic Salmon farms infected with *R. salmoninarum* 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 E).

On average, over two generations, juvenile and adult Fraser River Sockeye Salmon could encounter *R. salmoninarum*-infected Atlantic Salmon farms in the Discovery Islands area in six and seven of the eight years, respectively. 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 16% and 32% for juvenile and adult Fraser River Sockeye Salmon, respectively (see Appendix E).

Despite potential exposure in consecutive years, the likelihood assessment concluded that it was extremely unlikely for Fraser River Sockeye Salmon to become infected with *R. salmoninarum* attributable to Atlantic Salmon farms in the Discovery Islands area under current management practices.

4.3 ASSUMPTIONS

- There is no correlation between BKD 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 6 illustrates potential outcomes of spread and establishment resulting from at least one Fraser River Sockeye Salmon infected with *R. salmoninarum* released from infected Atlantic Salmon on farms located in the Discovery Islands area.

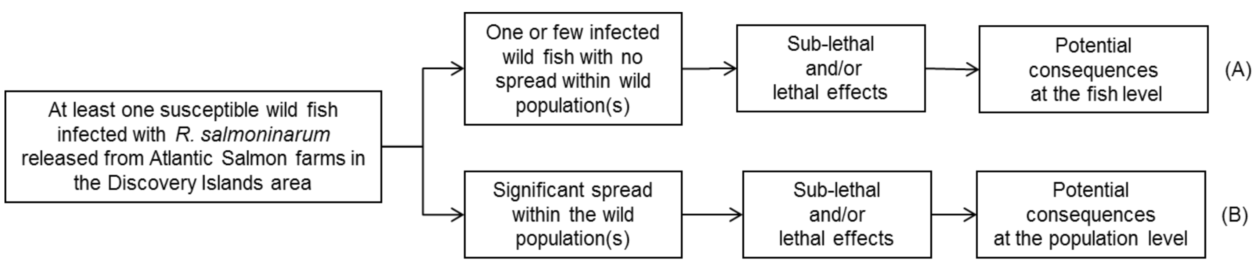

Figure 6. Potential outcomes resulting from at least one susceptible wild fish infected with Renibacterium salmoninarum *released from Atlantic Salmon farms located in the Discovery Islands area.*

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 *R. salmoninarum* infected Atlantic Salmon on four farms was assessed for juvenile and adult Fraser River Sockeye Salmon. 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 *R. salmoninarum*-infected Atlantic Salmon farms in the Discovery Islands area during their out-migration in six of eight years (Table 11). There is a 16% probability of exposure to infected farms that could occur over at least four consecutive years, over two generations (section 4.2.7). In years with infections, juveniles could be exposed to up to four *R. salmoninarum*-infected farms during their migration.

After migrating through the Discovery Islands area, juveniles will continue their migration through Johnstone Strait, Queen Charlotte Strait, and into the open ocean. Despite potential exposure, the likelihood assessment concluded that it was extremely unlikely for juvenile Fraser River Sockeye Salmon to become infected with *R. salmoninarum* attributable to Atlantic Salmon farms in the Discovery Islands area under current management practices. Nevertheless, the potential for an infection theoretically acquired in the Discovery Islands area to spread to other juvenile Fraser River Sockeye Salmon during migration at sea (Figure 6, Outcome A) was considered.

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 freshwater laboratory studies in Chinook Salmon, the time between exposure to waterborne *R. salmoninarum* and mortality is approximately 80 days (Murray et al., 1992) at a concentration over four orders of magnitude higher than the concentration estimated in net pens. It is therefore probable that an infected juvenile Fraser River Sockeye Salmon would only develop signs of *R. salmoninarum* infection attributed to a farm once 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).

There are no experimental data under varying population densities during BKD outbreaks; however, density was correlated with infection prevalence in free-ranging populations of Chinook Salmon in Puget Sound (Rhodes et al., 2011). As an indication of the impact of BKD resulting from spread in the population at farm densities, the 21-day rolling average daily mortality varied between 0.01 and 0.04% at the farm level over a period of a few months before and during the FHEs attributed to BKD on Atlantic Salmon farms in the Discovery Islands area, suggesting limited spread even at higher densities than those estimated for Sockeye Salmon in the open ocean.

Consequently, it is concluded that it is not plausible for juvenile Fraser River Sockeye Salmon exposed to the estimated concentrations of *R. salmoninarum* released from infected Atlantic Salmon farms (see section 3.4.2.4) to result in an infection that would spread and establish within the population. This is primarily based on the biology of *R. salmoninarum*. 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 that available data can only be used with caveats. Additionally, potential intergenerational effects are recognized but at this time there are no data to evaluate their potential impacts.

4.4.2 Adult Fraser River Sockeye Salmon

Adult Fraser River Sockeye Salmon are expected to encounter *R. salmoninarum*-infected Atlantic Salmon farms in the Discovery Islands area during their returning migration in seven of eight years. There is a 32% probability that exposure to infected farms could occur over at least four consecutive years over two generations (section 4.2.7). In years with infections, adults could be exposed to up to three infected farms during their migration.

After migrating through the Discovery Islands area, adult Fraser River Sockeye Salmon will continue their migration through the Strait of Georgia and up the Fraser River. Despite potential exposure, the likelihood assessment concluded that it was extremely unlikely for adult Fraser

River Sockeye Salmon to become infected with *R. salmoninarum* attributable to Atlantic Salmon farms in the Discovery Islands area under current management practices. Nevertheless, the potential for an infection theoretically 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 the spawning grounds and the Strait of Georgia ranges from 40 km for the Widgeon Slough population to 1,200 km for the Early Stuart population (Cohen, 2012b). In a fish health study, Early Stuart River Sockeye Salmon took up to about a month to reach spawning grounds (Stoddard, 1993). As stated above, laboratory studies estimate the time between exposure and mortality for Chinook Salmon to be 80 days when exposed to 3×10^4 *R. salmoninarum* cells/mL (3×10^{10} cells/m^3) (Murray et al., 1992), a concentration over four orders of magnitude higher than the estimated concentration on infected Atlantic Salmon farms in the Discovery Islands area. This is corroborated by the manner in which the disease is often characterized, specifically by slow bacterial growth (see Rhodes and Mimeault (2019)). Therefore, the time required from exposure to a low concentration of *R. salmoninarum* from infected farms to spawning is unlikely to be sufficient to allow for disease development.

The use of an epidemiological model to determine the potential spread on a *R. salmoninarum* infection acquired in the Discovery Islands area in returning adults was considered but determined not to be necessary given the lack of examples of disease outbreaks in the wild and the chronic nature of the of *R. salmoninarum* infections.

It was therefore concluded that the potential magnitude of consequences to the abundance or diversity of Fraser River Sockeye Salmon resulting from a *R. salmoninarum* infection of adult Fraser River Sockeye Salmon attributable to Atlantic Salmon farms in the Discovery Islands area under the current fish health management practices would be **negligible.** This conclusion was made with **reasonable uncertainty** given the use of surrogate data related to incubation time. Additionally, potential intergenerational effects are recognized but at this time there are no data to evaluate their potential impacts.

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 a *R. salmoninarum* infection of other susceptible Pacific salmon 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 to 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 **high uncertainty** given the lack of data on the impact that *R. salmoninarum*-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 *R. salmoninarum* attributable to Atlantic Salmon farms in the Discovery Islands area (Table 15) 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 15. Risk estimates to the abundance of Fraser River Sockeye Salmon resulting from Renibacterium salmoninarum *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	Extremely unlikely	Negligible	Minimal
Adult Fraser River Sockeye Salmon	Extremely 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 *R. salmoninarum* 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 a *R. salmoninarum* 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 *R. salmoninarum* attributable to Atlantic Salmon farms in the Discovery Islands area (Table 16) 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 16. Risk estimates to the diversity of Fraser River Sockeye Salmon resulting from Renibacterium salmoninarum *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	Extremely unlikely	Negligible	Minimal
Adult Fraser River Sockeye Salmon	Extremely 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 *R. salmoninarum* 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 a *R. salmoninarum* 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 information about the prevalence of *R. salmoninarum*-infected Atlantic Salmon on farms in the Discovery Islands area and the subsequent need to rely on expert opinion;
- the lack of information about shedding rates in *R. salmoninarum* infected and diseased farmed Atlantic Salmon;
- the lack of information about the minimum infectious and lethal doses of *R. salmoninarum* in Sockeye Salmon;
- the lack of information and variability in current data with respect to juvenile Fraser River Sockeye Salmon migration routes 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 *R. salmoninarum* 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 absence of BKD mortality data in wild Pacific salmon populations, and subsequent reliance on proxy mortality rates calculated from FHEs on Atlantic Salmon farms;
- the lack of knowledge of the consequences to individuals and populations of Sockeye Salmon resulting from sub-lethal infection with *R. salmoninarum*; and
- the consequences to subsequent generations related to the presence of *R. salmoninarum* in spawning populations.

7 CONCLUSIONS

The assessment concluded that *R. salmoninarum* 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 extremely unlikely that susceptible fish would become infected with *R. salmoninarum* released from an Atlantic Salmon farm located in the Discovery Islands area. Second, even in the extremely unlikely event that wild susceptible fish would become infected with *R. salmoninarum* due to Atlantic Salmon farms in the Discovery Islands area, 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 *R. salmoninarum* 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 the prevalence of *R. salmoninarum*-infected Atlantic Salmon on farms in the Discovery Islands area, shedding rates in *R. salmoninarum* carriers, heavily infected and diseased salmon; interaction of wild populations with Atlantic Salmon farms, and minimum infectious and lethal dose of *R. salmoninarum* in Sockeye Salmon and other susceptible species; and (2) consequence assessment for which there are no data on BKD 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

Balfry, S. K., Albright, L. J. and Evelyn, T. P. T. 1996. Horizontal transfer of *Renibacterium salmoninarum* among farmed salmonids via the fecal-oral route. Dis. Aquat. Org. 25(1-2): 63-69.

Banner, C. R., Long, J. J., Fryer, J. L. and Rohovec, J. S. 1986. Occurrence of salmonid fish infected with *Renibacterium salmoninarum* in the Pacific Ocean. J. Fish Dis. 9(3): 273-275.

BC Centre for Aquatic Health Sciences. 2010. Evaluation of bacterial kidney disease (BKD) impacts on the Canadian salmon aquaculture industry: Final report. Cambell River, BC. 70 p.

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.

Bell, G. R. 1961. Two epidemics of apparent kidney disease in cultured pink salmon (*Oncorhynchus gorbuscha*). J. Fish. Res. Board Can. 18(4): 559-562.

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.

Bruno, D. W. 1988. The relationship between auto-agglutination, cell surface hydrophobicity and virulence of the fish pathogen *Renibacterium salmoninarum*. FEMS Microbiol. Lett. 51(2-3): 135-139.

Bullock, G. L., Stuckey, H. M. and Mulcahy, D. 1978. Corynebacterial kidney disease: egg transmission following iodophore disinfection. Fish Health News 7(2): 51-52.

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

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

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

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

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

Cudmore, B., Mandrak, N. E., Dettmers, J., Chapman, D. C. and Kolar, C. S. 2012. Binational Ecological Risk Assessment of Bigheaded Carps (*Hypophthalmichthys* spp.) for the Great Lakes Basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/114. vi + 57 p.

Daly, J. G. and Stevenson, R. M. 1987. Hydrophobic and haemagglutinating properties of *Renibacterium salmoninarum.* J. Gen. Microbiol. 133: 3575-3580.

Daly, J. G. and Stevenson, R. M. 1989. Agglutination of salmonid spermatozoa by *Renibacterium salmoninarum.* J. Aquat. Anim. Health 1(2): 163-164.

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.

Elliott, D. G. and Pascho, R. J. 1995. Juvenile fish transportation: impact of bacterial kidney disease on survival of spring/summer Chinook salmon stock. 1993 Annual Report for the U.S. Fish & Wildlife Service. U.S. Army Corps of Engineers. Walla Walla, WA, USA.

Evelyn, T. P. T., Ketcheson, J. E. and Prosperi-Porta, L. 1984. Further evidence for the presence of *Renibacterium salmoninarum* in salmonid eggs and for the failure of povidine-iodine to reduce the intra-ovum infection in water-hardened eggs. J. Fish Dis. 7(3): 173-182.

Evelyn, T. P. T., Prosperi-Porta, L. and Ketcheson, J. E. 1986. Experimental intra-ovum infection of salmonid eggs with *Renibacterium salmoninarum* and vertical transmission of the pathogen with such eggs despite their treatment with erythromycin. Dis. Aquat. Org. 1(3): 197-202.

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

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.

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.

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.

Griffiths, S. G., Melville, K. J. and Salonius, K. 1998. Reduction of *Renibacterium salmoninarum* culture activity in Atlantic salmon following vaccination with avirulent strains. Fish Shellfish Immunol. 8(8): 607-619.

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.

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.

Kent, M. L., Traxler, G. S., Kieser, D., Richard, J., Dawe, S. C., Shaw, R. W., Prosperi-Porta, G., Ketcheson, J. and Evelyn, T. P. T. 1998. Survey of salmonid pathogens in ocean-caught fishes in British Columbia, Canada. J. Aquat. Anim. Health 10(2): 211-219.

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.

Mahony, A. M., Johnson, S. C., Neville, C. M., Thiess, M. E. and Jones, S. R. M. 2017. *Myxobolus arcticus* and *Parvicapsula minibicornis* infections in sockeye salmon *Oncorhynchus nerka* following downstream migration in British Columbia. Dis. Aquat. Org. 126(2): 89-98.

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.

McKibben, C. L. and Pascho, R. J. 1999. Shedding of *Renibacterium salmoninarum* by infected Chinook salmon *Oncorhynchus tschawytscha*. Dis. Aquat. Org. 38: 75-79.

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

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.

Murray, A. G., Munro, A. L. S., Wallace, I. S., Peeler, E. J. and Thrush, M. A. 2011. Bacterial kidney disease: assessment of risk to Atlantic salmon farms from infection in trout farms and other sources. *In* Scottish Marine and Freshwater Science. Aberdeen, UK. 2: 84 p.

Murray, A. G., Munro, L. A., Wallace, I. S., Allan, C. E. T., Peeler, E. J. and Thrush, M. A. 2012. Epidemiology of *Renibacterium salmoninarum* in Scotland and the potential for compartmentalised management of salmon and trout farming areas. Aquaculture 324: 1-13.

Murray, C. B., Evelyn, T. P. T., Beacham, T. D., Barner, L. W., Ketcheson, J. E. and Prosperi-Porta, L. 1992. Experimental induction of bacterial kidney disease in chinook salmon by immersion and cohabitation challenges. Dis. Aquat. Org. 12: 91-96.

Nance, S. L., Riederer, M., Zubkowski, T., Trudel, M. and Rhodes, L. D. 2010. Interpreting dual ELISA and qPCR data for bacterial kidney disease of salmonids. Dis. Aquat. Org. 91(2): 113-119.

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.

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.

Purcell, M. K., McKibben, C. L., Pearman-Gillman, S., Elliott, D. G. and Winton, J. R. 2016. Effects of temperature on *Renibacterium salmoninarum* infection and transmission potential in Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). J. Fish Dis. 39(7): 787-798.

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.

Rhodes, L. D. and Mimeault, C. 2019. Characterization of *Renibacterium salmoninarum* and bacterial kidney disease to inform pathogen transfer risk assessments in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/018. vi + 46 p.

Rhodes, L. D., Rice, C. A., Greene, C. M., Teel, D. J., Nance, S. L., Moran, P., Durkin, C. A. and Gezhegne, S. B. 2011. Nearshore ecosystem predictors of a bacterial infection in juvenile Chinook salmon. Mar. Ecol. Prog. Ser. 432: 161-172.

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.

Salonius, K., Siderakis, C., MacKinnon, A. M. and Griffiths, S. G. 2005. Use of *Arthrobacter davidanieli* as a live vaccine against *Renibacterium salmoninarum* and *Piscirickettsia salmonis* in salmonids. Dev. Biol. (Basel) 121: 189-197.

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.

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.

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 BKD 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, 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 17). 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, a total of 13 audit-based farm-level diagnoses of BKD were reported on six Atlantic Salmon farms in the Discovery Islands area, the last two occurred in 2009 (Table 17).

Table 17. Summary of active Atlantic Salmon farms, number of audits conducted and audits with farm-level bacterial kidney disease (BKD) 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 BKD diagnoses	Number of audited farms with farm-level BKD diagnoses
2002	NA	3	3	NA	1	1
2003	NA	10	4	NA	0	0
2004	14	13	9	64	1	1
2005	15	18	11	73	4	3
2006	16	19	12	75	4	3
2007	16	24	13	81	1	1
2008	17	28	15	88	0	0
2009	18	23	14	78	2	2
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**	**---**	**---**	**13**	**6**

Detection of *R. salmoninarum* or *Renibacterium*-like organisms in the absence of other evidence of disease, is not sufficient to trigger a farm-level diagnosis of BKD. Therefore, low levels of *R. salmoninarum* may be present in farmed populations and these are only detectable using sensitive diagnostic methods. Data from the BC provincial and DFO Health Audit and Surveillance Program conducted on Atlantic Salmon farms in the Discovery Islands area between 2002 and 2016 which document findings indicative of *R. salmoninarum* infection are summarized in Table 17.

Since 2002, there have been a total of 13 audit-based farm-level BKD diagnoses:

- In 2002 on Freddie Arm in October;
- In 2004 on Shaw Point in August;
- In 2005 on three farms: Althorpe in June, Chancellor in February and Philips Arm in May and July;
- In 2006 on three farms: Chancellor in January and May; Lees Bay in May and Shaw Point in September;
- In 2007 on Lees Bay in February; and
- In 2009 on two farms: Althorpe in January and Chancellor in April.

In addition to the above farm-level diagnoses, there was confirmation of *R. salmoninarum* and/or BKD infection identified or diagnosed through histology in a total of 23 audits:

- In 2002, *R. salmoninarum* was identified through histopathology on Raza during a November audit (number of fish unspecified).
- In 2003, *R. salmoninarum* and possible signs of BKD were identified through histological diagnosis on Raza during a February audit (number of fish unspecified).
- In 2004, *R. salmoninarum* was identified through histopathology on two farms; Brent Island during a July audit and Lees Bay during an August audit (number of fish unspecified).
- In 2006, *R. salmoninarum* was identified through histopathology on two farms: Althorpe during a November audit (in one of seven fish) and Lees Bay during a May audit (in 14 of 15 fish).
- In 2008, *R. salmoninarum* was identified through histopathology on three farms; Brougham during an April audit (in one of five fish), Cyrus Rocks during an April audit (in the only fish sampled) and Farside during a December audit (in one of seven fish). Furthermore, BKD was diagnosed through histopathology on three farms in that year; Freddie Arm during a September audit (in one of six fish), Hardwicke during the January (in one of five fish) and April audits (in three of four fish) and Sonora Point during a July audit (in one of four fish).
- In 2009, *R. salmoninarum* was identified through histopathology on two farms; Brougham during a January audit (number of fish unspecified) and Freddie Arm during a March audit (in one of four fish).
- In 2012, clinical signs of BKD were identified and *Renibacterium*-like bacteria were identified through histological diagnosis on four farms; Althorpe in July and October (in six of 14 fish), Cyrus Rocks during an April audit (in two of six fish), Sonora/Okisollo during a July audit (in one of three fish) and Thurlow during a January audit (in one of four fish).
- In 2013, signs of BKD with *Renibacterium*-like bacteria were identified through histological diagnosis on Sonora/Okisollo during a January audit (in one of three fish).
- In 2014, signs of BKD with *Renibacterium*-like bacteria were identified through histological diagnosis on two farms; Hardwicke during an April audit (in one of three samples) and Venture (months unspecified, in one of 25 fish).

- In 2016, signs of BKD with *Renibacterium*-like bacteria were identified through histological diagnosis on Phillips Arm during an August audit (in one of seven fish).

All farm-level diagnoses of BKD from 2002 to 2016 occurred on facilities located in Frederick Arm, Phillips Arm and the Northwestern channels. *Renibacterium salmoninarum* was not detected by audit on Barnes Bay or Bickley farms from 2002 to 2016.

Table 18. Results of government fish health audits (2002-2016) conducted on Atlantic Salmon farms in the Discovery Islands area in which Renibacterium salmoninarum *and/or bacterial kidney disease (BKD) were detected. Testing for* R. salmoninarum *through histopathology was conducted on all carcasses collected through the FHASP (2011-2016). For audits where the number of fish with histologic diagnosis of BKD and/or* R. salmoninarum *was not clearly reported, ≥1 is noted to indicate a minimum of one fish carcass. The * indicates that results only mention* R. salmoninarum *in the histopathology report without mention of BKD. Source: DFO Aquaculture Management for provincial fish health audits (2002-2010) and DFO (2018c) for DFO fish health audits (2011-2016).*

Year	Facility Name	# of fish health audits	Number of carcasses assessed	Number of fish with histologic diagnosis of BKD with *Renibacterium* -like bacteria	Farm-level veterinary diagnosis
2002	Freddie Arm	1	20	≥1	BKD
	Raza	1	7	≥1*	Open
2003	Raza	2	11	≥1	Open (audit #1); Algal bloom (audit #2)
2004	Brent Island	3	18	≥1*	Post vaccination peritonitis (audit #1); Open (audit # 2, 3)
	Lees Bay	2	17	≥1*	Bacteremia (audit #1); Dual diagnosis: Open and Post vaccination peritonitis (audit #2)
	Shaw Point	1	4	≥1*	BKD
2005	Althorpe	1	6	≥1*	BKD
	Chancellor	1	2	≥1*	BKD
	Phillips Arm	2	15	≥1*	BKD (audit #1, 2)
2006	Althorpe	2	9	1*	Open
	Chancellor	2	13	5*	BKD (audit #1, 2)
	Lees Bay	3	30	15*	Open (audit #1); BKD (audit #2); Algal bloom (audit #3)
	Shaw Point	1	8	≥1*	BKD
2007	Lees Bay	4	34	5*	BKD (audit #1); Open (audit # 2, 3, 4)
2008	Brougham	2	7	1*	Open - no known cause/ no significant lesions
	Cyrus Rocks	2	7	1*	Open - no known cause/ no significant lesions (audit #1); Mouth rot (audit #2)
	Farside	1	7	1*	Open - no known cause/ no significant lesions
	Freddie Arm	3	13	1	Open - no known cause/ no significant lesions
	Hardwicke	2	9	4	Open - no known cause/ no significant lesions
	Sonora Point	2	5	1	Open - no known cause/ no significant lesions

Year	Facility Name	# of fish health audits	Number of carcasses assessed	Number of fish with histologic diagnosis of BKD with *Renibacterium* -like bacteria	Farm-level veterinary diagnosis
2009	Althorpe	2	13	≥1	BKD (audit #1); Open - no known cause/no significant lesions (audit #2)
	Brougham	1	4	≥1*	Other
	Chancellor	1	10	7	BKD
	Freddie Arm	1	4	1*	Open - no known cause/ no significant lesions
2012	Althorpe	3	14	6	No disease significant at the population level
	Cyrus Rocks	3	15	2	No disease significant at the population level
	Sonora Island	3	7	1	No disease significant at the population level
	Thurlow	1	4	1	No disease significant at the population level
2013	Sonora Island	1	3	1	No disease significant at the population level
2014	Hardwicke	1	3	1	No disease significant at the population level
	Venture	3	25	1	No disease significant at the population level
2016	Phillips Arm	2	12	1	No disease significant at the population level

9.2 APPENDIX B: FISH HEALTH EVENTS

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

Between 2002 and 2017, a total of 10 FHEs attributed to BKD were reported by industry on Atlantic Salmon farms in the Discovery Islands area. They were reported during the months of February, March, April, June and October, however it is not possible to attribute seasonality due to the small number of FHEs. Additionally, although FHEs provide disease distribution information such as presence/absence in time (season) and place (Fish Health Surveillance Zone) they are not amenable to statistical treatment such as trend analyses and should be interpreted with caution.

*Table 19. Number of active Atlantic Salmon farms in the Discovery Islands area and fish health events (FHEs) attributed to bacterial kidney disease (BKD) 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 (for 2013-2015 FHEs). * seven different farms.*

Year	Number of active farms	Number of FHEs attributed to BKD	Number of farms that reported FHEs attributed to BKD
2002	NA	0	0
2003	NA	0	0
2004	14	0	0
2005	15	6	5
2006	16	0	0
2007	16	0	0
2008	17	2	1
2009	18	1	1
2010	16	1	1
2011	17	0	0
2012	13	0	0
2013	8	0	0
2014	10	0	0
2015	10	0	0
2016	11	0	0
2017	12	0	0
Total	**--**	**10**	**8***

9.3 APPENDIX C: INDUSTRY SURVEILLANCE AND DETECTIONS

Table 20 summarizes observations by fish health staff made during site visits and sampling for *R. salmoninarum*/BKD diagnostic tests on Atlantic Salmon farms in the Discovery Islands area. Observations and samplings were performed for a variety of reasons, including routine health checks, screening of fish (including broodstock kept in marine net pens), investigations of elevated mortality from various causes, and fish health investigations for research projects that include pathogen or disease screening.

As *R. salmoninarum* is endemic in the region and clinical signs and gross lesions of BKD are easily recognized by trained personnel, not every field observed BDK case on a farm is confirmed by laboratory tests. Therefore, industry data and observations of BKD lesions (or suspected of BKD) or mortalities have been summarized in addition to tests results. More specifically, explicit comments by fish health staff (including farm veterinarian) about the presence of any number of “BKD fish” has been tallied as evidence of the disease for the farm, even if the case was not confirmed by diagnostic testing.

All laboratory test results targeting *R. salmoninarum* (ELISA, PCRs) or indicative of *R. salmoninarum* and/or BKD (histology, tissue imprints) were tallied. Tissue imprints and histology indicating a positive result for either *R. salmoninarum* or BKD were considered as evidence of *R. salmoninarum* infection or disease. Inconclusive lab results (e.g., ELISA “suspect”) were considered negative.

The industry detected the presence of *R. salmoninarum* and/or BKD in Atlantic Salmon marine farms located in the Discovery Islands area every year between 2011 and 2017 (Table 20). The pathogen and/or disease have been reported year-round by the industry. Frequency of occurrence differs between farms and years, but may partly reflect variations in site production and fish health monitoring and management practices. One farm reported no cases of BKD and no detections of *R. salmoninarum* despite screening for the pathogen over the period.

Table 20. Summary of industry Renibacterium salmoninarum *detections and/or bacterial kidney disease (BKD) diagnoses between 2011 and 2017 on Atlantic Salmon farms in the Discovery Islands area. Data include observations by fish health staff reporting at least one fish with macroscopic BDK lesions during a site visit and diagnostic laboratory results for* R. salmoninarum *and/or BKD. Diagnostic laboratory tests include histology, tissue imprints, ELISA and PCR.*

Year	Number of site visits with		Number of farms with	
	evidence of *R. salmoninarum* and/or BKD	testing for *R. salmoninarum* and/or BKD	evidence of *R. salmoninarum* and/or BKD	testing for *R. salmoninarum* and/or BKD
2011	18	72	11	14
2012	13	43	5	8
2013	7	15	3	7
2014	7	38	2	7
2015	3	29	2	7
2016	2	63	2	11
2017	11	48	4	10

9.4 APPENDIX D: PROPORTION OF POPULATION POTENTIALLY EXPOSED

This appendix details the estimation of the proportion of the Fraser River Sockeye Salmon population, juveniles and adults, that could be in the Discovery Islands area at the same time as *R. salmoninarum* infections and/or BKD 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 during periods when *R. salmoninarum* infections and/or BKD have been detected on one or more farms.

9.4.1 Juveniles

The proportion of juvenile Sockeye Salmon that could be exposed to *R. salmoninarum*-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 *R. salmoninarum* 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 2011, May and June had infected farms and received their respective weights of 30% and 62%, but July was 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 92%.

Table 21. Estimated proportion of juvenile lake-type Fraser River Sockeye Salmon that could potentially have been exposed to Renibacterium salmoninarum*-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	1	0.00	0.00	0.08	0.08
2005	1	1	1	0.30	0.62	0.08	1.00
2006	1	0	0	0.30	0.00	0.00	0.30
2007	0	0	0	0.00	0.00	0.00	0.00
2008	0	0	1	0.00	0.00	0.08	0.08
2009	0	0	0	0.00	0.00	0.00	0.00
2010	0	0	0	0.00	0.00	0.00	0.00
2011	1	1	0	0.30	0.62	0.00	0.92
2012	1	1	1	0.30	0.62	0.08	1.00
2013	1	0	1	0.30	0.00	0.08	0.38
2014	0	1	1	0.00	0.62	0.08	0.70
2015	1	1	0	0.30	0.62	0.00	0.92
2016	0	1	0	0.00	0.62	0.00	0.62
2017	1	0	0	0.30	0.00	0.00	0.30

With the evidence of *R. salmoninarum* 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 *R. salmoninarum* was released from Atlantic Salmon farms between 2002 and 2017 (16 years) in the Discovery Islands area ranged between 0 and 100% (median=30% and mean=39%).

However, in the consequence assessment, the years without evidence of infection (total of five years) have to be disregarded given the assumption that "at least one migratory fish has been infected with the *R. salmoninarum* 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 (11 years), the proportion of juvenile Fraser River Sockeye Salmon that could have been in the Discovery Islands area when *R. salmoninarum* was released from Atlantic Salmon farms ranged between 8 and 100% (median=62% and mean=57%). These estimates are based on the evidence of *R. salmoninarum* occurrences summarized in Table 11.

9.4.2 Adults

The proportion of adult Sockeye Salmon that could be exposed to *R. salmoninarum*-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 *R. salmoninarum* 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. 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. Refer to Mimeault et al. (2020) for details.

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 2014, June, July and August had infected farms and received their respective weights of 0.3%, 12.2%, and 79.7% but September and October were not infected. Therefore, the sum of the five weighted-months (92.2%) multiplied by the NDR for the year (96%) resulted in an estimate of the proportion of adults that could potentially have been exposed in this year to be 89% (Table 22).

The proportion of returning adult Fraser River Sockeye Salmon that could have been in the Discovery Island area when *R. salmoninarum* 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 89% (median=7% and mean= 21%).

When only considering the 13 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 Island area when *R. salmoninarum* was released from Atlantic Salmon farms during their return migration ranged between approximately zero and 89% (median=14% and mean= 26%). These estimates are based on evidence of *R. salmoninarum* occurrences including detections at the fish level summarized in Table 11.

Table 22. Estimated proportion of adult Fraser River Sockeye Salmon that could potentially have been exposed to Renibacterium salmoninarum-*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 the 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 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 of weighted presence/ absence	NDR	Proportion of adults potentially exposed
	Jun	Jul	Aug	Sep	Oct	Jun	Jul	Aug	Sep	Oct			
2002	0	0	0	0	1	0	0	0	0	0.001	0.001	0.51	0.001
2003	0	0	0	0	0	0	0	0	0	0	0	0.69	0
2004	0	1	1	0	0	0	0.122	0.797	0	0	0.919	0.64	0.59
2005	1	1	0	0	0	0.003	0.122	0	0	0	0.125	0.74	0.09
2006	0	0	0	1	0	0	0	0	0.077	0	0.077	0.65	0.05
2007	0	0	0	0	0	0	0	0	0	0	0	0.44	0
2008	0	1	0	1	0	0	0.122	0	0.077	0	0.199	0.10	0.02
2009	0	0	0	0	0	0	0	0	0	0	0	0.47	0
2010	0	0	0	0	1	0	0	0	0	0.001	0.001	0.73	0
2011	1	0	1	0	1	0.003	0	0.797	0	0.001	0.801	0.62	0.50
2012	1	1	1	0	1	0.003	0.122	0.797	0	0.001	0.923	0.18	0.17
2013	0	1	0	1	0	0	0.122	0	0.077	0	0.199	0.71	0.14
2014	1	1	1	0	0	0.003	0.122	0.797	0	0	0.922	0.96	0.89
2015	1	0	0	0	0	0.003	0	0	0	0	0.003	0.69	0.002
2016	1	0	1	0	0	0.003	0	0.797	0	0	0.8	0.50	0.40
2017	0	0	1	0	1	0	0	0.797	0	0.001	0.798	0.71	0.57

9.5 APPENDIX E: EXPOSURE OVER TWO GENERATIONS

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

9.5.1 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 out of the 16 years in which evidence of *R. salmoninarum* and/or BKD has been recorded on farms between 2002 and 2017, 11 and 13 years reported evidence during the months when, respectively, juvenile and adult Fraser River Sockeye Salmon are expected in the Discovery Islands area (Table 11). In other words, in any given year, the probability that juveniles could be in the Discovery Islands at the same time as a farm is infected with *R. salmoninarum* is, on average, 69% (11/16). Similarly, in any given year, the probability that adults could be in the Discovery Islands at the same time as a farm is infected with *R. salmoninarum* is on average 81% (13/16).

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) = 0.6875 for juveniles and 0.8125 for adults, and
- number of trials (n) = eight years, representing two generations of Fraser River Sockeye Salmon.

9.5.1.1 Juveniles

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

- On average, 5.5 years out of the eight years (mean = n × P = 8 × (11/16) = 5.5, with SD = $\sqrt{n \times p \times (1-p)}$ = 1.3).
- Figure 7 provides the complementary cumulative distribution (CCDF), from which the probability of potential exposure in at least a given number of years is illustrated. For example, the probability that juveniles become exposed in at least two out of eight years is 99%, while the probability that juveniles become exposed in at least five out of eight years is 52%, and so on.
- Over one generation (four years), the probability of exposure in four consecutive years is 22% (P^4 = 0. 6875^4 = 0.22).
- Over two generations, the probability of exposure 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 could be exposed to *R. salmoninarum* released from infected Atlantic Salmon farms in the Discovery Islands area in at least four consecutive years over two generations is 15.6% (Table 23).

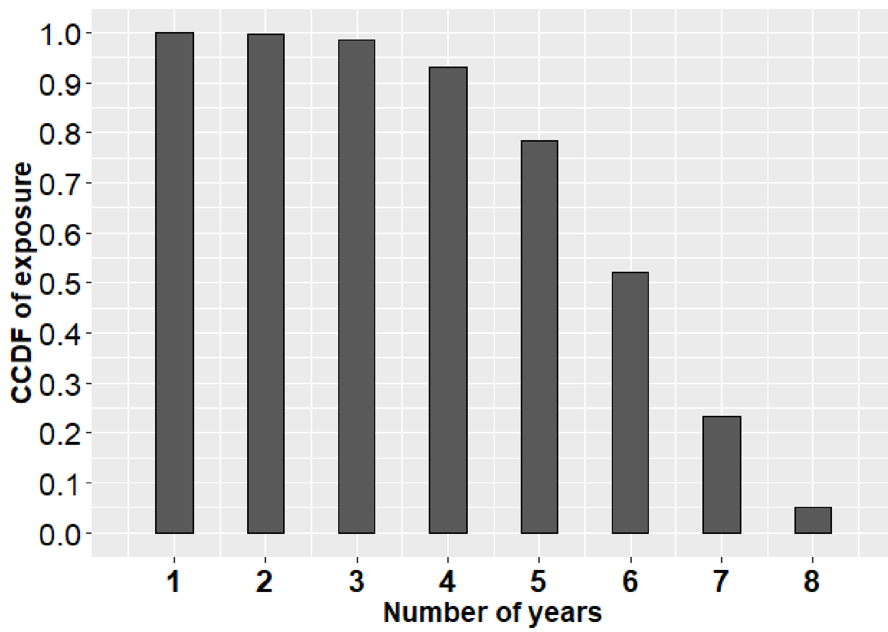

Figure 7. Complementary cumulative probability distribution (CCDF) of potential exposure of juvenile Fraser River Sockeye Salmon to Renibacterium salmoninarum*-infected Atlantic Salmon farms in the Discovery Islands area over eight years.The probability of exposure is based on a binomial process assuming a probability of success (p) of 0.6875, and a number of trials (n) of eight years.*

Table 23. Probability of exposure of juvenile Fraser River Sockeye Salmon to Renibacterium salmoninarum *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 0.6875 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	0.1491	5	70	0.0107
5	8	0.2625	4	56	0.0187
6	8	0.2887	3	28	0.0309
7	8	0.1815	2	8	0.0454
8	8	0.0499	1	1	0.0499
Probability of at least four consecutive years in two generations (eight years)					**0.1556**

** 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.*

9.5.1.2 Adults

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

- On average, 6.5 years out of the 8 years (mean = n × P = 8 × (13/16) = 6.5, with SD = $\sqrt{n \times p \times (1 - p)}$ = 1.1).
- Figure 8 provides the complementary cumulative distribution (CCDF), from which the probability of exposure in at least a given number of years is illustrated. For example, the probability that adults become exposed in at least two out of eight years is 99%, while the probability that adults become exposed in at least five out of eight years is 82%, and so on.
- Over one generation (four years), the probability of exposure in four consecutive years is 44% ($mean^4$ = and $0.8125^4 = 0.44$).
- Over two generations, the probability of exposure in at least four consecutive years over eight years is determined as above for the juveniles. Consequently, the probability that adults could be exposed to *R. salmoninarum* released from infected Atlantic Salmon farms in the Discovery Islands area in at least four consecutive years over two generations is 32% (see Table 24).

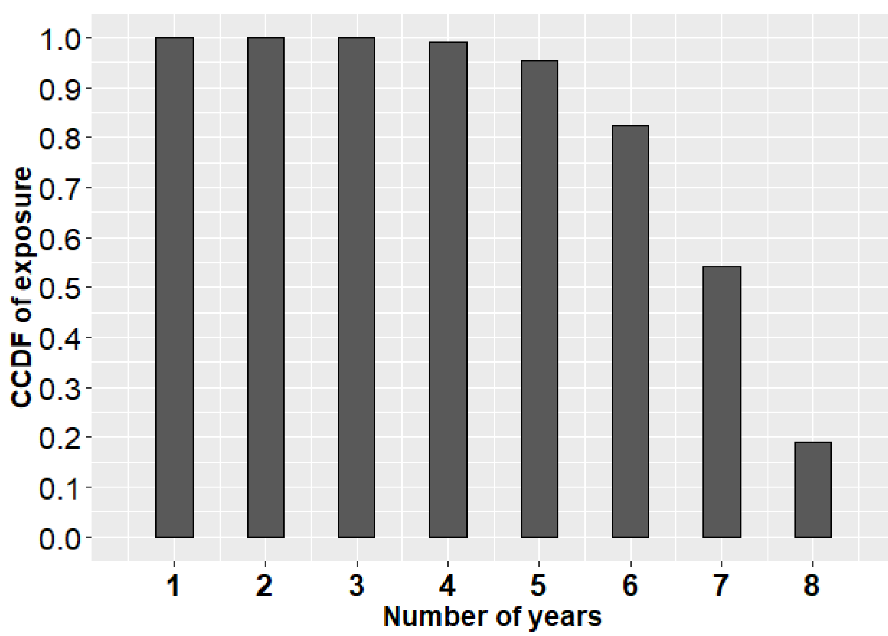

Figure 8. Complementary cumulative probability distribution (CCDF) of potential exposure of adult Fraser River Sockeye Salmon to Renibacterium salmoninarum*-infected Atlantic Salmon farms in the Discovery Islands area over eight years. The probability of exposure is based on a binomial process assuming a probability of success (p) of 0.8125, and a number of trials (n) of eight years.*

Table 24. Probability of exposure of adult Fraser River Sockeye Salmon to Renibacterium salmoninarum *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 0.8125 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	0.1307	4	56	0.0093
6	8	0.2832	3	28	0.0303
7	8	0.3506	2	8	0.0877
8	8	0.1899	1	1	0.1899
Probability of at least four consecutive years in two generations (eight years)					**0.3200**

** 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.*

9.5.2 Simulation approach

To further evaluate the reliability of the exposure estimates from the binomial process, a simulation approach was also 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 *R. salmoninarum* and/or showing clinical signs of BKD.

The resulting frequency distributions of the sums are compared with the results of the binomial process (Table 25). The two approaches resulted in very close results, indicating 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 25 for examples).

Table 25. 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 (%)	Adults (%)
At least five	Binomial process	78	95
	Bootstrap (1,000)	78	94
	Bootstrap (10,000)	78	95
At least six	Binomial process	52	83
	Bootstrap (1,000)	52	82
	Bootstrap (10,000)	52	83