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

Canadian Science Advisory Secretariat (CSAS)

Research Document 2020/065

National Capital Region

Assessment of the risk to Fraser River Sockeye Salmon due to viral haemorrhagic septicaemia virus IVa (VHSV-IVa) transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia

G.J. Parsons[1*], I.J. Burgetz[1*], L. Weber[1*], K.A. Garver[2], S.R.M. Jones[2], S. Johnson[2], L.M. Hawley[2], B. Davis[3], P. Aubry[4], J. Wade[5] and C. Mimeault[1]

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

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

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

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

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

*co-leads

January 2021

Foreword

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

Published by:

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

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

ISSN 1919-5044

Correct citation for this publication:

Parsons, G.J., Burgetz, I.J., Weber, L., Garver, K.A., Jones, S.R.M., Johnson, S., Hawley, L.M., Davis, B., Aubry, P., Wade, J. and Mimeault, C. 2021. Assessment of the risk to Fraser River Sockeye Salmon due to viral haemorrhagic septicaemia virus IVa (VHSV-IVa) transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/065. viii + 36 p.

Aussi disponible en français :

Parsons, G.J., Burgetz, I.J., Weber, L., Garver, K.A., Jones, S.R.M., Johnson, S., Hawley, L.M, Davis, B., Aubry, P., Wade, J. et Mimeault, C. 2021. Évaluation du risque pour le saumon rouge du fleuve Fraser attribuable au transfert du virus de la septicémie hémorragique virale IVa (vSHV-IVa) à partir des fermes d'élevage de saumon atlantique situées dans la région des îles Discovery (Colombie-Britannique). Secr. can. de consult. sci. du MPO. Doc. de rech. 2020/065. ix + 41 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

Clinical: outward appearance of a disease in a living organism

Disease: an abnormality of structure or function which results in measurable compromise in physiological or behavioral performance and is not a direct result of physical injury

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

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

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

Horizontal transmission: fish to fish transfer of a pathogen

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

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

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

Polymerase chain reaction (PCR): a method used in genetic analysis to rapidly make millions of copies of a specific DNA sample, allowing the use of a very small sample of DNA and to amplify it to a large enough amount in order to study it in detail

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

Reverse transcription PCR, or RT-PCR: allows the use of RNA as a template. An additional step in which the RNA is reverse transcribed into complementary DNA (cDNA), using reverse transcriptase allows for the detection and quantification of RNA. From here on, the standard PCR procedure is used to amplify the cDNA

Silvers: recently deceased fish or fresh fish mortalities

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

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

ABSTRACT

Fisheries and Oceans Canada (DFO), under the Aquaculture Science Environmental Risk Assessment Initiative, is conducting a series of assessments to determine potential 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 potential risk to Fraser River Sockeye Salmon due to viral haemorrhagic septicaemia virus IVa (VHSV-IVa) on Atlantic Salmon farms in the Discovery Islands area of BC under current farm practices. All the VHSV detected in BC belong to the genotype IVa, therefore, this risk assessment focuses only on the risk associated with genotype IVa. The assessment was conducted in three main steps: (1) likelihood assessment which includes four consecutive steps (farm infection, release, exposure, and infection assessments); (2) consequence assessment; and (3) risk estimation.

Viral haemorrhagic septicaemia virus has occasionally been reported on Atlantic Salmon farms in BC between 2002 and 2019, it is therefore unlikely, with reasonable certainty, that Atlantic Salmon infected with VHSV would be present on one or more Atlantic Salmon farm(s) in the Discovery Islands area in any given year. Despite knowledge gaps around the infection dynamics and shedding rates of VHSV in Atlantic Salmon, it was concluded that the release of the virus from infected farms was extremely likely, with high certainty, given evidence of horizontal transmission of the virus in cohabitation trials. However, the release of the virus through vectors or fomites is unlikely, with reasonable certainty, under the current farm practices given that effective biocontainment measures are in place.

It was concluded that the likelihood of juvenile Fraser River Sockeye Salmon to be exposed to VHSV through seawater during migration was unlikely, with a reasonable certainty, given the limited temporal overlap between Fraser River Sockeye Salmon and occurrence of VHSV on farms. Of the five years (out of 18; 2002-2019) in which VHSV was reported, only one year had evidence of VHSV during the time period that juveniles migrate through the Discovery Islands area. For adult Fraser River Sockeye Salmon, it was concluded that the likelihood of exposure to VHSV through seawater during migration was extremely unlikely, with a high certainty, given there was no temporal overlap between the migrating adults and the occurrence of VHSV on Atlantic Salmon farms in the Discovery Island area.

It was concluded that the likelihood of juvenile and adult Fraser River Sockeye Salmon to become infected with VHSV is extremely unlikely with reasonable certainty given that Sockeye Salmon are not susceptible to VHSV infections.

As the consequences are dependent on the susceptibility of Sockeye Salmon, the magnitude of consequences to the abundance and diversity of Fraser River Sockeye Salmon are both estimated as negligible. As Sockeye Salmon are not susceptible to VHSV infections, without infection, there will be no consequence (which is captured in the negligible consequence category) to the abundance and diversity of Fraser River Sockeye Salmon attributable to Atlantic Salmon farms in the Discovery Islands area.

Overall, the assessment concluded that VHSV 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.

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.

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, 2012).

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

This document assesses the risk to Fraser River Sockeye Salmon (*Oncorhynchus nerka*) attributable to viral haemorrhagic septicaemia virus IVa (VHSV-IVa), the causative agent of viral haemorrhagic septicaemia (VHS), on Atlantic Salmon farms in the Discovery Islands area in BC. All the VHSV detected in BC belong to the genotype IVa (Garver et al., 2013b); therefore, the risk assessment focuses only on this genotype. Risk posed to other wild fish populations and related to other fish farms, pathogens, and regions of BC are not included in this analysis.

2 BACKGROUND

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

The Framework ensures the delivery of systematic, structured, transparent and comprehensive risk assessments. It is consistent with international and national risk assessment frameworks (GESAMP, 2008; ISO, 2009) and has been validated through multiple peer-reviewed processes (Mimeault et al., 2017; Mimeault et al., 2019; Mimeault et al., 2020a; Mimeault et al., 2020b; Mimeault et al., 2020c; Mimeault et al., 2020d; Mimeault et al., 2020e; Mimeault et al., 2020f). The Framework includes the identification of management protection goals, a problem formulation, a risk assessment and the generation of science advice. The management protection goals and problem formulation were developed in collaboration with DFO's Ecosystems and Oceans Sciences and Ecosystem and Fisheries Management sectors and approved by Aquaculture Management Division.

The Framework also comprises risk communication and a scientific peer-review through DFO's Canadian Science Advisory Secretariat (CSAS) that includes scientific experts both internal and external to DFO. Further details about the Initiative and the Framework are available on the DFO Aquaculture Science Environmental Risk Assessment Initiative webpage. Risk assessments conducted under this Initiative do not include socio-economic considerations and are not cost-benefit or risk-benefit analyses.

2.1 MANAGEMENT PROTECTION GOALS

In accordance with the recommendations pertaining to aquaculture and fish health in the 2012 final report of the Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (Cohen, 2012), 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 viral haemorrhagic septicaemia virus attributable to Atlantic Salmon farms in the Discovery Islands area.

2.2.2 Hazard characterisation

Viral haemorrhagic septicaemia virus (VHSV) is the causative agent of the disease viral haemorrhagic septicaemia (VHS) which can occur in a wide range of wild and farmed fish species in both marine and freshwater environments (Kocan et al., 1997; Marty et al., 1998; Lovy et al., 2012; Garver et al., 2013b). It is an endemic pathogen in marine waters in BC where it is frequently detected in Pacific Herring (*Clupea pallasii pallasii*) and Pacific Sardines (*Sardinops sagax*) (summarized in Garver and Hawley (2021)).

Garver and Hawley (2021) summarized the relevant characteristics of VHSV and VHS and identified knowledge gaps relevant to this risk assessment. They also included a review of the occurrence of VHS on Atlantic Salmon farms in BC. Additional details including evidence of VHSV specific to Atlantic Salmon farms located in the Discovery Islands area are included in this risk assessment.

Viral haemorrhagic septicaemia is on the list of the World Organisation for Animal Health notifiable diseases (OIE, 2016) and is a reportable disease in Canada. Consequently, all suspected and confirmed cases must be immediately reported to the Canadian Food Inspection Agency (CFIA).

Phylogenetic analyses have classified VHSV isolates into four major genotypes (I, II, III and IV) and ten subtypes (Ia-If and IVa-IVd) which to some degree correlate with geographical distributions (Einer-Jensen et al., 2004; Elsayed et al., 2006; Guðmundsdóttir et al., 2019). In addition, genotypes also appear to have some differentiation concerning pathogenicity and host range associations. All the VHSV detected in BC belong to the genotype IVa (Garver et al., 2013b). Therefore, in this risk assessment, our focus is on the studies that involve the genotype IVa where available.

2.2.3 Scope

This assessment aims to determine the risk under current farm practices, including regulatory requirements and voluntary practices as described in Wade (2017). It focuses on the risk attributable to Atlantic Salmon farms in the Discovery Islands area (Fish Health Surveillance Zone 3-2) and in close proximity (three farms in 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 all prior pathogen transfer risk assessments within this series (Mimeault et al., 2017; Mimeault et al., 2019; Mimeault et al., 2020a; Mimeault et al., 2020b; Mimeault et al., 2020c; Mimeault et al., 2020d; Mimeault et al., 2020e; Mimeault et al., 2020f). 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.

Although 18 farms are included, it is worth noting that from December 2010 to February 2016, the number of stocked Atlantic Salmon farms ranged between three and 18, with an average of eight farms in any given month (Mimeault et al., 2017).

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

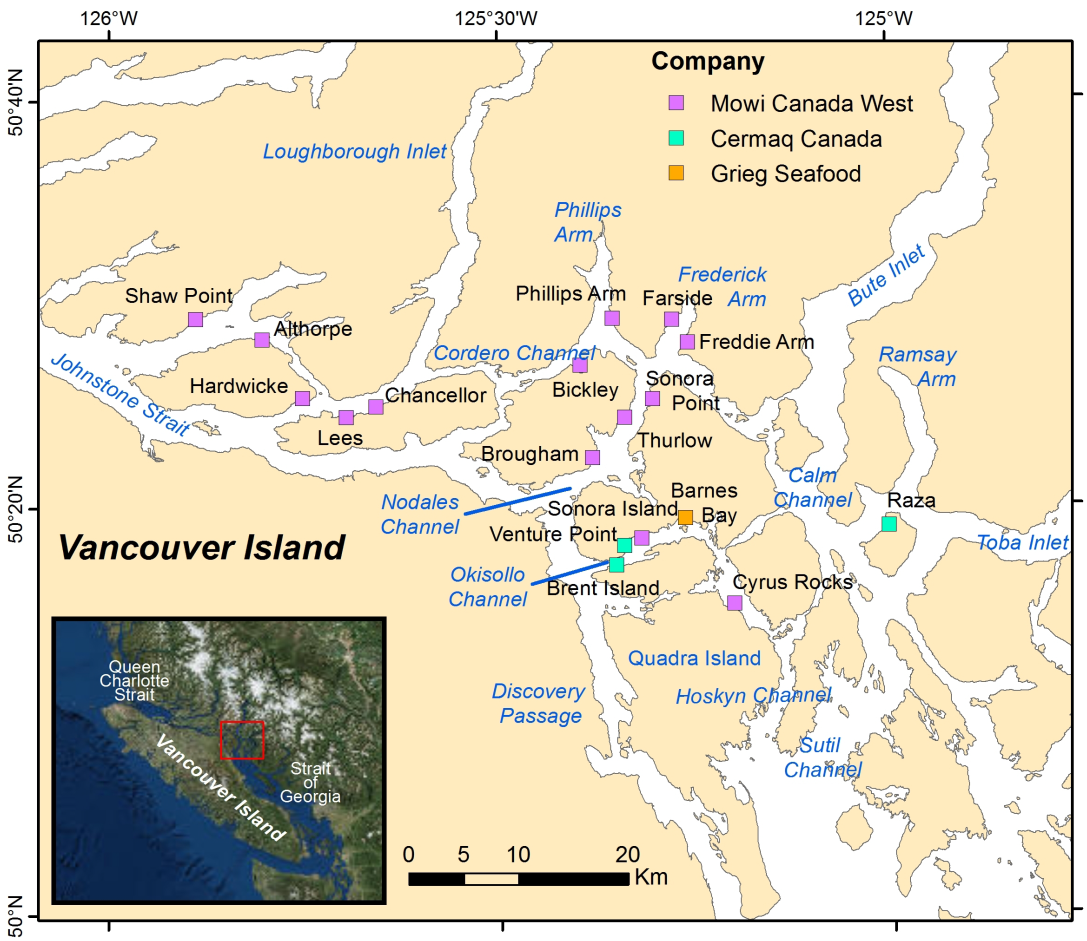

Figure 1. Locations of Atlantic Salmon farms in the Discovery Islands area (Fish Health Surveillance Zone 3-2 and three farms in Fish Health Surveillance Zone 3-3) included in this risk assessment. Symbol size for fish farms is not to scale. Different colours represent different companies operating the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

Table 1. List of the 18 Atlantic Salmon farms included in the risk assessment. Note that Althorpe, Hardwicke and Shaw Point are officially licensed in Fish Health Surveillance Zone 3.3 but are grouped with farms in Fish Health Surveillance Zone 3.2 for the purpose of this risk assessment and as per Aquaculture Management reporting practices.

Company	Farm	Licensed in 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 VHSV-IVa from Atlantic Salmon farms located in the Discovery Islands area under current farm practices?

2.2.5 Methodology

The methodology is based on Mimeault et al. (2017), which was adapted from the DFO Guidelines for Assessing the Biological Risk of Aquatic Invasive Species in Canada (Mandrak et al., 2012), the World Organisation for Animal Health (OIE) Import Risk Analysis (OIE, 2010), recommendations for risk assessments in coastal aquaculture (GESAMP, 2008) and the Food and Agriculture Organisation guidelines on understanding and applying risk analysis in aquaculture (FAO, 2008). This methodology was consistently used in previous pathogen transfer risk assessments for Fraser River Sockeye Salmon conducted by DFO (Mimeault et al., 2019; Mimeault et al., 2020a; Mimeault et al., 2020b; Mimeault et al., 2020c; Mimeault et al., 2020d; Mimeault et al., 2020e; Mimeault et al., 2020f).

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 (Figure 3 and Figure 4) to estimate the risk.

The likelihood is assessed in four consecutive steps, namely: a farm infection assessment; a release assessment; an exposure assessment; and an infection assessment. The consequence assessment determines the potential magnitude of impacts of VHSV infection attributable to Atlantic Salmon farms in the Discovery Islands area on the abundance and diversity of Fraser River Sockeye Salmon.

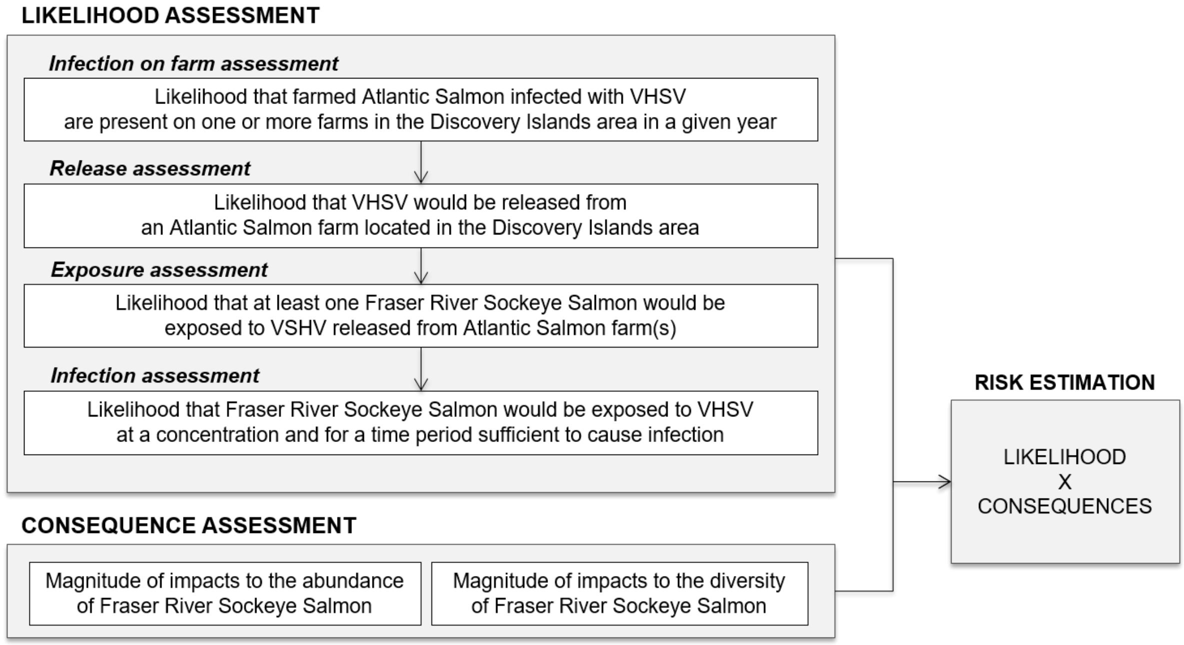

Figure 2. Conceptual model to assess the risks to Fraser River Sockeye Salmon due to viral haemorrhagic septicaemia virus (VHSV) on Atlantic Salmon farms located in the Discovery Islands area, British Columbia. Adapted from Mimeault et al. (2017).

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 taken or adapted from Mimeault et al. (2017) and Mimeault et al. (2019).

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. Taken from Mimeault et al. (2019).

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

Table 3. Categories and definitions used to describe the potential consequences to the abundance of Fraser River Sockeye Salmon. Taken from Mimeault et al. (2019).

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. One Fraser River Sockeye Salmon generation is four years. CU: Conservation Unit. Taken from Mimeault et al. (2019).

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 scientific data and information. Adapted from Mimeault et al. (2019).

Categories	Definitions
High uncertainty	• No or insufficient data • Available data are of poor quality • Very high intrinsic variability • There is no consensus in the scientific literature
Reasonable uncertainty	• Limited, incomplete, or only surrogate data are available • Available data can only be reported with significant caveats • Moderate to high intrinsic variability • Scientific literature and/or models come to different conclusions
Reasonable certainty	• Available data are abundant, but not comprehensive • Available data are robust • Low intrinsic variability • Scientific literature 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 • Scientific literature and/or models agree

Table 6. Categories and definitions used to describe the level of uncertainty associated with fish health management on farms. "Some" and "most" are, respectively, defined as less and more than 50% of relevant data. Adapted from Mimeault et al. (2019).

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) • Fish health professionals' opinions vary 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) • Fish health professionals 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 • Fish health professionals 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 • Fish health professionals agree

2.2.5.3 Ranking attribution

Attribution of rankings was done in a multi-step, structured approach. First, drafts of both the pathogen paper (Garver and Hawley, 2021) and this risk assessment (without ranking attribution) were distributed to the authors of the risk assessment. Then, authors individually ranked each step of the risk assessment and assigned an uncertainty level. Finally, ranking results and rationales were discussed during a series of conference calls in which the consensus included in this risk assessment was reached.

2.2.5.4 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 ranking might underestimate the overall likelihood.

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

2.2.5.5 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 Aquatic 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.

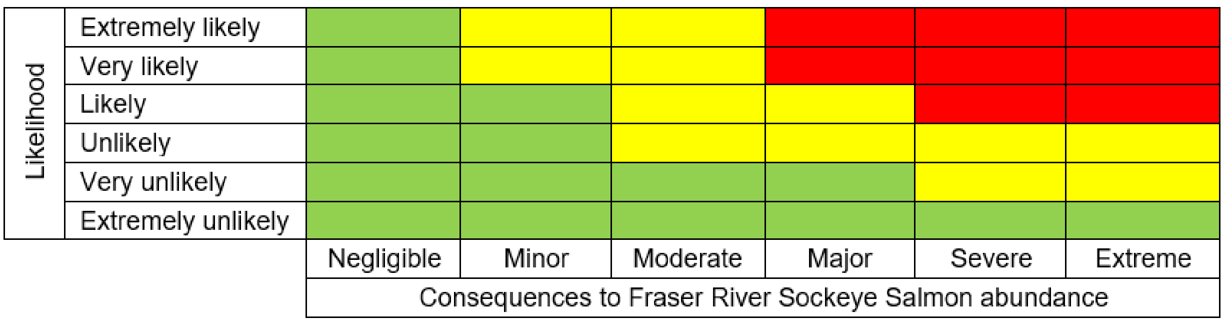

Figure 3. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon abundance. Green, yellow and red represent minimal, moderate and high risk, respectively.

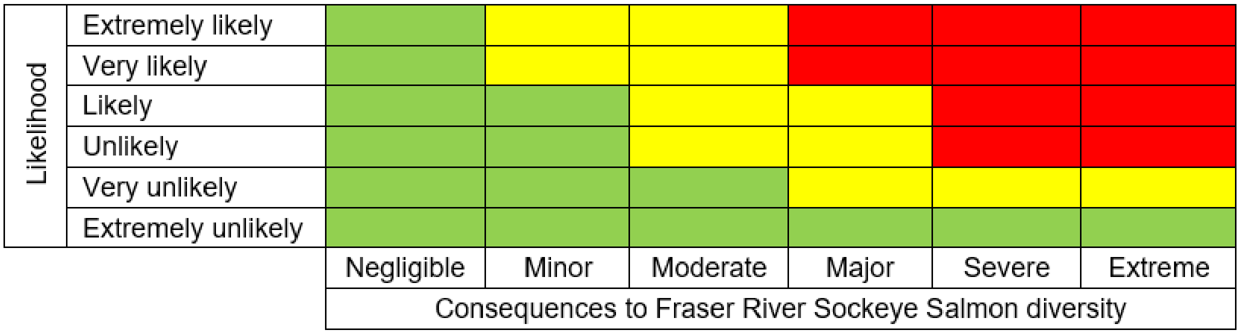

Figure 4. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon diversity. Green, yellow and red represent minimal, moderate and high risk, respectively.

2.3 SOURCES OF FISH HEALTH DATA

This risk assessment relies on the current state of knowledge related to VHSV as summarised in Garver and Hawley (2021). Fish health data on Atlantic Salmon farms in the Discovery Islands area used to inform this assessment are from four different sources summarized below.

2.3.1 Industry

The industry provided data collected by fish health staff during site visits for routine health checks, investigations of elevated mortality, fish health events and projects on Atlantic Salmon farms in the Discovery Islands area between 2011 and 2019 to inform pathogen transfer risk assessments in the Discovery Islands area.

2.3.2 Fish Health Audit and Surveillance Program

Under the Fish Health Audit and Surveillance Program (FHASP), “VHS is diagnosed in a farmed Atlantic Salmon population if there is population-level mortality attributable to the disease with gross pathological and histopathological lesions consistent with the disease: characteristic gross pathology includes subcutaneous haemorrhage and darkening of the skin.”

Samples from recently dead fish are collected through the FHASP to audit the routine monitoring and reporting of diseases by the farms (Wade, 2017). 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, 2020c).

Audit data were compiled from BC Ministry of Agriculture and Lands (2002-2010) and from DFO data available on the Open Canada website (2011-2018) (downloaded on March 16, 2020) (DFO, 2020c).

2.3.3 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, and submit a notification of FHE and therapeutic management measures to the Department (DFO, 2015).

Reporting of FHEs has been required since the autumn of 2002 with the exception of 2013, 2014 and first three quarters of 2015 during which mortalities had to be reported by cause (DFO, 2015; 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. Our analysis included the following datasets:

- 2002-2010: from the BCSFA;
- 2011-2012: provided by Aquaculture Management Division;
- 2013-2015: provided by the BCSFA; and
- 2016-2019: available on the Open Canada website (downloaded on March 16, 2020) (DFO, 2020a).

2.3.4 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).

Mortality events reporting between 2002-2010 was required but details and reports are not available; 2011-2019 data are published on the Open Canada website (downloaded on March 16, 2020) (DFO, 2020b).

2.4 REGULATORY REQUIREMENTS

2.4.1 Licensing and biosecurity

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

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

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

2.4.2 Introduction and Transfer Committee

DFO grants Introduction and Transfer licenses under Section 56 of the Fishery (General) Regulations. The ITC assesses the health, genetic and ecological impacts that could occur through the transfer of fish into and within the Province. A Section 56 introductions and transfers licence is required for all movements of salmon between licensed aquaculture facilities (DFO, 2018). For the aquaculture industry, the committee assesses the health of fish to be transferred which includes the diseases and causative agents of regional, national or international concern as listed in Appendix III[1] of the Marine Finfish Aquaculture Licence under the Fisheries Act, in addition to any other disease or indication of poor health status as determined by fish health expert(s) sitting on the Introductions and Transfers Committee. This would include gross signs of disease caused by VHSV including haemorrhaging of the skin, lethargy, and darkening of the skin.

Viral haemorrhagic septicaemia (VHS) is a reportable disease in Canada and therefore any suspicion of VHSV or positive detection must be immediately reported to the CFIA, who would then be the lead federal authority in any follow-up actions required. In the case of VHS, the CFIA does not impose movement restrictions for the VHSV-IVa strain in BC. However, the ITC would prohibit the transfer of any population experiencing or exposed to clinical VHS, including situations where wild Pacific Herring in or near a farmed salmon population are experiencing a VHS outbreak. In the rare occurrence of VHS on farm, it is a disease that tends to quickly resolve on its own without intervention in a matter of weeks in farmed salmon (B. Boyce, Mowi Canada West, 124-1334 Island Highway, Campbell River, BC V9W 8C9, pers. comm., 2020) and therefore the recommendation of the ITC would be to delay any transfer until the population no longer had clinical disease or exposure to clinical disease. A polymerase chain reaction (PCR) detection of VHSV during routine screening may occur without any indication of disease in the population. In those instances, the ITC would require additional testing and monitoring to ensure the prevalence of infection is very low and no clinical disease is present in the population prior to making any recommendation to transfer.

For every freshwater to marine finfish aquaculture-related transfer application, industry is required to conduct routine fish health testing, including for VHSV. The fish health testing results, fish health reports and husbandry records are examined by Aquaculture Management Division staff prior to transfer. If any clinical signs of diseases are seen, or there are any other concerns, the committee is notified and may seek clarification, require further diagnostics or additional information from the applicant, compel mitigation to address concerns, and/or recommend the transfer licence is not issued.

2.4.3 Canadian Food Inspection Agency

Under the Health of Animals Act, VHS is a federally reportable disease and anyone who owns or works with aquatic animals and knows of or suspects VHS must notify the CFIA.

The CFIA then initiates an investigation dependent on the declared disease status related to the notification. Part of the determination of their response measures is whether the facility is in an

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

area the CFIA has deemed to be "infected" or "free" for the disease. The Pacific Ocean watershed of BC, which includes the Discovery Islands area, is an infected area for VHSV-IVa. Refer to the CFIA webpage on Aquatic animal disease investigation and response for more details on the VHS control program.

Since 2012, the CFIA has published monthly reports of confirmations of federally reportable aquatic animal health diseases by date, province and species on their website. Confirmations of VHS in BC can be found on the CFIA webpage on Locations infected with viral haemorrhagic septicaemia. As data are only reported at the provincial level these data could not be used in this risk assessment.

2.5 INDUSTRY PRACTICES

Wade (2017) provides an overview of health management practices on Atlantic Salmon farms in BC. While industry has implemented new practices since 2017, they are not of consequence to the control and management of VHSV infection and VHS on Atlantic Salmon farms.

2.5.1 Fish health management practices

Wade (2017) reviewed all common health management practices on Atlantic Salmon farms in BC including a coordinated industry response should a viral outbreak occur. A brief description of the most relevant practices to our risk assessment is presented in this section. As part of regulatory requirements under the Conditions of Licence, several fish health management practices are mandatory, and these are described below. As outlined under Section 2.4.1, 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). A SOP for fish disease outbreaks or emergency, where an outbreak is defined as an "unexpected occurrence of mortality or disease" is also required (DFO, 2015).

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

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

Compliance with the above elements is determined through FHASP. On average, less than one deficiency per audit has been reported on Atlantic Salmon farms in BC between 2011 and 2017 (Wade, 2017; Mimeault et al., 2019). Most deficiencies reported in this period were related to sea lice protocols and sea lice records; carcass retrieval protocol or record keeping that requires improvement; mooring signage needing improvement; and transfer records not being complete.

2.5.2 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 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. 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 PCR testing (for infectious haematopoietic necrosis virus (IHNV), VHSV, and *Piscirickettsia salmonis*) and three fish are submitted for full histology examination (B. Milligan, Cermaq Canada, 203-919 Island Highway, Campbell River, BC 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).

2.5.3 Stocking practices in the Discovery Islands area

In the Discovery Islands area, smolts are not transferred directly from freshwater hatcheries to marine sites due to the risk of infection from *Kudoa* sp., a parasite of marine fishes (Wade, 2017) with the exception of Raza, where *Kudoa* sp. has not been an issue (D. New, Cermaq Canada, 203-919 Island Highway, Campbell River, BC V9W 2C2, pers. comm., 2018). In other words, the majority of farmed Atlantic Salmon reared in the Discovery Islands area are raised in a marine nursery site outside the area before being transferred to the final grow-out site.

Fish transfers to marine grow-out sites in the Discovery Islands area occurred every month of the year (Mimeault et al., 2019). Fish reared in the Discovery Islands area can spend between two and 14 months (average of seven months, n=23 cycles) on a marine nursery site outside the Discovery Islands area before being transferred to a grow-out site in the area (Mimeault et al., 2019).

3 LIKELIHOOD ASSESSMENT

The likelihood assessment determines the overall likelihood, in any given year, that Fraser River Sockeye Salmon would become infected with VHSV 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 VHSV are present on one or more farms in the Discovery Islands area?

3.1.2 Considerations

Considerations include the evidence of the occurrence of VHSV on Atlantic Salmon farms in the Discovery Islands area, and industry practices specific to the prevention and control of VHSV.

3.1.2.1 Viral haemorrhagic septicaemia virus on Atlantic Salmon farms in the Discovery Islands area

Viral haemorrhagic septicaemia diagnoses and VHSV detections on Atlantic Salmon farms in the Discovery Islands area were compiled from the sources of data listed in Section 2.3.

Although the detection of VHSV in an individual fish is not necessarily equivalent to clinical disease in that fish or at the population level, it can be indicative of the greater presence of infection on the farm.

3.1.2.1.1 Industry

Between 2011 and 2019, VHSV was detected once per year by RT-PCR in three different years on Atlantic Salmon farms in the Discovery Island area (Table 7, Appendix).

3.1.2.1.2 Fish Health Audit and Surveillance Program (FHASP)

Throughout BC, a total of 17 farm-level VHS diagnoses have been reported through FHASP on Atlantic Salmon farms between 2002 and 2018 (Garver and Hawley, 2021).

In the Discovery Islands area, between 2002 and 2018, VHSV was detected through PCR in three years (2003, 2005 and 2012) and identified through histology in one year (2012). VHS has not been diagnosed at the farm level in the Discovery Island area as part of the FHASP (Table 7).

3.1.2.1.3 Fish Health Events

Throughout BC, a total of 17 FHEs attributed to VHS have been reported on Atlantic Salmon farms between 2002 and 2019 [Q2] but excluding 2013-2015 as reporting was not required during those years (Garver and Hawley, 2021).

In the Discovery Islands area, one FHE attributed to VHS was reported on an Atlantic Salmon farm (2003).

Overall, FHEs attributed to VHS on Atlantic Salmon farms in the Discovery Islands area have been reported in 1 out of 18 years (Table 7).

3.1.2.1.4 Mortality Events

Between 2011 and 2019, one mortality event attributed to VHS has been reported in BC. The event occurred in March 2012 on an Atlantic Salmon farm located in Fish Health Surveillance Zone 3.3 (Broughton Archipelago) (DFO, 2020b).

No mortality events attributed to VHS, or to any other infectious diseases, have been reported on Atlantic Salmon farms in the Discovery Islands area between 2011 and 2019 [Q1] (DFO, 2020b).

3.1.2.1.5 Summary

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

Table 7 summarizes all evidence of VHSV on Atlantic Salmon farms in the Discovery Islands area by year. Overall, between 2002 and 2019, VHS was diagnosed or VHSV was detected on Atlantic Salmon farms in the Discovery Islands area in a total of five years.

It is acknowledged that the detection of a pathogen in an individual fish does not imply clinical signs or disease in a population.

Table 7. Number of Atlantic Salmon farms in the Discovery Islands area with evidence of viral haemorrhagic septicaemia virus (VHSV) and viral haemorrhagic septicaemia (VHS) summarized by year. Data include industry detections by reverse transcriptase polymerase chain reaction (RT-PCR) (2011-2019), Fish Health Audit and Surveillance Program (FHASP) (2002-2018), fish health events (FHEs) (2002-2019 [Q2]), and mortality events (2011-2019 [Q1]) reported by the industry to DFO. NA: not available. Years with evidence of VHSV are bolded and shaded.

Year	Active farms	Industry Data	Reported by industry to DFO		FHASP data		
		Number of farms with positive PCR samples	Number of farms with FHEs attributed to VHS	Number of farms with mortality events attributed to VHS	Number of farms with positive VHSV PCR samples/ total number of farms audited	Number of farms with VHSV identified through histology/ total number of farms audited	Number of farms with farm-level VHS diagnoses / total number of farms audited
2002	NA	NA	0	NA	0/3	0	0/3
2003	NA	NA	**1**	NA	**1/4**	0	0/4
2004	14	NA	0	NA	0/9	0	0/9
2005	15	NA	0	NA	**1/10**	0/10	0/10
2006	16	NA	0	NA	0/11	0/11	0/11
2007	16	NA	0	NA	0/12	0/12	0/12
2008	17	NA	0	NA	0/14	0/14	0/14
2009	18	NA	0	NA	0/14	0/14	0/14
2010	16	NA	0	NA	0/16	0/16	0/4
2011	17	0/17	0	0	0/7	0/7	0/7
2012	13	**1/13**	0	0	**1/12**	**1/12**	0/12
2013	8	0/8	0	0	0/7	0/7	0/7
2014	10	**1/10**	0	0	0/8	0/8	0/8
2015	10	**1/10**	0	0	0/9	0/9	0/9
2016	11	0/11	0	0	0/11	0/11	0/11
2017	12	0/12	0	0	0/9	0/9	0/9
2018	10	0/10	0	0	0/9	0/9	0/9
2019	12	0/12	0	0	NA	NA	NA

3.1.2.2 Preventive and control measures

In addition to industry preventative practices described in Section 2.5, the SOPs on the farm are good general practices for limiting stress and minimizing pathogen transfer; this is presumed to also limit the contracting and spreading of VHS and VHSV. Further, some of the common chemicals used in the aquaculture industry as disinfectants include Virkon® Aquatic, Peroxigard™, chlorine compounds and hydrogen peroxide chemicals. These have been shown to be efficacious at rendering VHSV inactive when it is exposed at the prescribed concentration for the required contact time (summarized in Bovo et al. (2005) and Bowker et al. (2019)). More specifically, a 0.5 to 1% Virkon® Aquatic solution disinfects field gear and hard surfaces from VHSV after 10 minutes of contact time (Bowker et al., 2019). All companies rearing Atlantic Salmon in the Discovery Islands use Virkon® Aquatic (Wade, 2017).

There is no treatment for VHS. Any suspicion of VHSV or positive test must be immediately reported to the CFIA who would then be the lead federal authority in any follow-up actions required. In the case of VHS in BC, the goal of the CFIA control program is geographic containment of the disease rather than eradication given that the VHSV-IVa strain is considered endemic in this area. The ITC may, however, impose movement restrictions within the geographic area.

VHS rarely, if ever, occurs on Atlantic Salmon farms (P. Whittaker, Grieg Seafood, pers. comm., 2020; B. Boyce, Mowi Canada West, pers. comm., 2020). On the rare occasion VHSV has been detected, it was a low level, isolated case and it resolved on its own within a matter of weeks (B. Boyce, Mowi Canada West, pers. comm., 2020).

3.1.2.3 Vaccination

Currently, there is no commercially available vaccine for VHS in Atlantic Salmon (Garver and Hawley, 2021).

3.1.3 Assumption

All detections of VHSV provide evidence of infection with VHSV.

3.1.4 Likelihood of farm infection

Table 8 presents the main factors contributing to and limiting the likelihood of a VHSV 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 viral haemorrhagic septicaemia virus (VHSV) are present on one or more farms in the Discovery Islands area under the current farm practices.

Contributing factors	Limiting factors
• Atlantic Salmon are first stocked in a marine nursery site before being transferred to the final grow-out site in the Discovery Islands area; • Between 2002 and 2019, VHSV was detected five times in 18 years by PCR on at least one Atlantic Salmon farm; • Between 2002 and 2019, one FHE was attributed to VHS (in 2003); and • There is no commercially available vaccine for VHS in Atlantic Salmon.	• DFO's Introduction and Transfer Committee requires testing before transfer permits are approved; • All Atlantic Salmon farming companies conduct diagnostic testing for VHSV through PCR prior to any live transfer; • Salmonid Health Management Plans include requirements for minimizing stress during transfer, handling and harvesting (DFO, 2015); and • There have been no mortality events reported by industry associated with VHS and no farm-level diagnoses for VHS reported under the FHASP (nine years).

It was concluded that, in a given year, the likelihood that farmed Atlantic Salmon infected with VHSV are present on one or more Atlantic Salmon farms in the Discovery Islands area is **unlikely** under the current farm practices, given evidence of VHSV in five years between 2002 and 2019 (over a total of 18 years). This conclusion was made with **reasonable certainty** given that the evidence is based on the detection of VHSV and clinical signs of VHS from FHASP, FHE reports and other sources over a period of 18 years (abundant and robust data) and low intrinsic variability in the data.

3.2 RELEASE ASSESSMENT

3.2.1 Question

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

3.2.2 Considerations

Considerations include Atlantic Salmon rearing method in the Discovery Islands area; transmission route; shedding of VHSV from infected fish; and fish health management practices (see Section 2.5.1). Two pathways are considered in the release assessment: (1) infected farmed Atlantic Salmon, and (2) mechanical vectors (e.g., personnel, visitors and wildlife) and fomites (e.g., farm equipment and vessels). VHSV release from Pacific Herring (*Clupea pallasii pallasii*) or other susceptible species in the vicinity of the net pens was not considered.

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 cages and there are no barriers to pathogen exchanges between the net pens and the surrounding environment (Johansen et al., 2011).

3.2.2.2 Transmission and shedding of VHSV

Garver and Hawley (2021) reviewed the state of knowledge related to transmission and shedding in VHSV-infected fish. Viral haemorrhagic septicaemia virus has been demonstrated to be transmitted through oral/ingestion route (Schönherz et al., 2012; Getchell et al., 2013), waterborne transmission (Lovy et al., 2013), vectors (Faisal and Schulz, 2009; Faisal and Winters, 2011), and fomites (Pham et al., 2012). However, waterborne transmission is likely the dominant route of VHSV infection, as laboratory studies have effectively transmitted the virus through either bath exposure or via cohabitation with infected fish (Lovy et al., 2013).

In instances where farmed Atlantic Salmon become infected with VHSV, the duration and extent of virus shedding from infected individuals is unknown. Several laboratory studies have been published which report virus shedding and transmission in Atlantic Salmon (Garver and Hawley, 2021). A laboratory study transmitting VHSV from Atlantic Salmon to Pacific Herring demonstrated that Atlantic Salmon are capable of shedding VHSV following infection and that levels of shed virus were sufficient enough to infect a highly susceptible species like Pacific Herring (Lovy et al., 2013). However, successful transmission of VHSV from Atlantic Salmon to Pacific Herring in laboratory trials has been inconsistent and likely reflects the limited susceptibility of Atlantic Salmon to VHSV (Garver and Hawley (2021)). Laboratory studies have also shown that VHSV can be retained on fomites such as plastic pieces, glass, and fishing lines; however, the duration for which VHSV remains infectious on the objects was dependent upon storage conditions and material type (Pham et al., 2012). When plastic, glass, and aluminum objects were stored in the dark under moist conditions, infectious virus could be retained for at least 10 days. However, when objects were stored under dry conditions, infectious virus was not recovered past the first sampling day (Pham et al., 2012).

3.2.3 Assumption

Atlantic Salmon infected with VHSV are present on at least one farm.

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 viral haemorrhagic septicaemia virus (VHSV) would be released from infected Atlantic Salmon farms in the Discovery Islands area into an environment accessible to Fraser River Sockeye Salmon under the current farm practices.

Contributing factors	Limiting factors
Infected farmed Atlantic Salmon	
• Horizontal transmission of VHSV has been shown in cohabitation trials; • Atlantic Salmon in the Discovery Islands area are reared in net pens allowing pathogens, including VHSV, to be released from the farms to the surrounding environment; and • There is no commercially available vaccine for VHSV in Atlantic Salmon.	• Regular removal of moribund and fresh dead fish from affected cages/farms; and • VHS is a disease that tends to quickly resolve on its own in Atlantic Salmon.
Mechanical vectors and fomites	
• Viral haemorrhagic septicaemia virus can remain infectious on surfaces of fomites depending on environmental conditions (Pham et al., 2012).	• Biocontainment protocols, including the use of effective disinfectants against VHSV, are in place to minimize pathogen spread on infected mechanical vectors and fomites (see section 2.5.1 and 3.1.2.2); and • On average, less than one deficiency has been reported per audit on Atlantic Salmon farms in BC between 2011 and 2017.

3.2.4.1 Release through infected farmed Atlantic Salmon

It was concluded that the likelihood that VHSV would be released from an infected Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to Fraser River Sockeye Salmon through infected farmed Atlantic Salmon is **extremely likely** under the current farm practices given the evidence of shedding under laboratory conditions. This conclusion was made with **high certainty** based on cohabitation trials, showing VHSV is transmitted from infected fish to naïve cohabitant fish through water.

3.2.4.2 Release through vectors and fomites

It was concluded that the likelihood that VHSV would be released from an infected Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to wild fish populations through vectors or fomites is **unlikely** under the current farm practices given that effective biocontainment measures are in place and low levels of operational deficiencies that could affect fish health on Atlantic Salmon farms. This conclusion was made with **reasonable certainty** given that relevant biosecurity practices are part of SHMP and hence licence requirements.

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 VHSV would be released from an infected Atlantic Salmon farm.

3.3 EXPOSURE ASSESSMENT

3.3.1 Question

Assuming that VHSV has been released from at least one Atlantic Salmon farm in the Discovery Islands area, what is the likelihood that at least one Fraser River Sockeye Salmon would be exposed to VHSV 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 timing of Fraser River Sockeye Salmon migration in the Discovery Islands area; timing of VHSV on Atlantic Salmon farms; temporal overlap between VHSV on farms and Fraser River Sockeye Salmon in the Discovery Islands area; size and volume of Atlantic Salmon farms; oceanographic and environmental conditions; and survival of VHSV in the marine environment.

3.3.2.1 Timing of Fraser River Sockeye Salmon in the Discovery Islands area

3.3.2.1.1 Out-migrating juveniles

Lake-type juvenile Fraser River Sockeye Salmon migrate through the Discovery Islands area every year from mid-May to mid-July, with a migration peak in June (Neville et al., 2016; Freshwater et al., 2019) (reviewed in Grant et al., 2018). The total number of juveniles out-migrating from the Fraser River, in any given year, is unknown (Grant et al., 2018). The only estimate of abundance is limited to stocks from Chilko Lake (Grant et al., 2018) based on smolts enumerated at a counting fence located at the outlet of the lake. Between 1953 and 2007, annual estimates ranged between 1.6 to 77 million (average: 20 million) (Grant et al., 2018).

3.3.2.1.2 Returning adults

Sockeye Salmon return to the Fraser River either through the northern route (Johnstone Strait) or the southern route (Strait of Juan de Fuca); typically, between June and October (reviewed in Grant et al., 2018). Between 1980 and 2014, the total adult returns of Fraser River Sockeye Salmon ranged from 2 to 28 million, with an annual average of 9.6 million (Grant et al., 2018).

3.3.2.2 Timing of viral haemorrhagic septicaemia virus on Atlantic Salmon farms

Table 10 summarizes VHSV detections and VHS diagnoses on Atlantic Salmon farms in the Discovery Islands area by month. There has been only one VHS-related FHE reported (May 2003).

Between 2002 and 2018, VHSV PCR detections by industry or through the FHASP occurred in January, February and April.

Overall, between 2002 and 2019, VHSV and VHS have been reported on Atlantic Salmon farms only during the period of January to May (Table 10 and Table 11).

Table 10. Summary of the evidence of temporal overlap between Fraser River Sockeye Salmon and viral haemorrhagic septicaemia virus (VHSV) and viral haemorrhagic septicaemia (VHS) occurrences on Atlantic Salmon farms in the Discovery Islands area. "X" indicates the presence of Fraser River Sockeye Salmon. Data include monthly results (summed over all available years) from the industry detections by polymerase chain reaction (PCR) (2011-2019) Fish Health Audit and Surveillance Program (FHASP) (2002-2018), fish health events (FHEs) (2002-2019) and mortality events (2011-2019) reported by the industry to DFO. Months with evidence of VHSV and/or VHS are shaded.

Fraser River Sockeye Salmon in the Discovery Islands area	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Lake-type juveniles	-	-	-	-	X	X	X	-	-	-	-	-
Returning adults	-	-	-	-	-	X	X	X	X	X	-	-
Evidence of VHSV on Atlantic Salmon farms in the Discovery Islands area	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Number of farms with positive detections of VHSV (industry)	**2**	0	0	**1**	0	0	0	0	0	0	0	0
Number of farms with positive VHSV PCR samples (FHASP)	0	**1**	0	**1**	0	0	0	0	0	0	0	0
Number of farms with VHSV identified through histology (FHASP)	0	0	0	**1**	0	0	0	0	0	0	0	0
Evidence of VHS on Atlantic Salmon farms in the Discovery Islands area	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Number of farms with farm-level VHS diagnoses	0	0	0	0	0	0	0	0	0	0	0	0
Number of farms with FHEs attributed to VHS	0	0	0	0	**1**	0	0	0	0	0	0	0
Number of farms with mortality events attributed to VHS	0	0	0	0	0	0	0	0	0	0	0	0

Fish Health Audit and Surveillance Program and FHE data were combined to determine the number of different farms with VHSV detections and/or VHS diagnoses for a given month and year (Table 11). A single farm might have contributed to more than one month within each year.

Table 11. Number of Atlantic Salmon farms in the Discovery Islands area with occurrences of viral haemorrhagic septicaemia virus (VHSV) and viral haemorrhagic septicaemia (VHS), between 2002 and 2019, summarized per year and month. Data include results from the Industry (2011-2019), Fish Health Audit and Surveillance Program (FHASP) (2002-2018) and Fish Health Events (FHEs) (2002-2019 [Q2]). No mortality events attributed to VHSV were reported (2011-2019 [Q1]) on Atlantic Salmon farms in the Discovery Islands area. Months with evidence of VHSV and/or VHS are shaded.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	0	0	0	0	0	0	0	0	0	0	0	0
2003	0	1	0	0	1	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0	0	0	0
2005	0	1	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0	0	0	0	0
2012	1	0	0	1	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0	0	0	0	0
2014	0	0	0	1	0	0	0	0	0	0	0	0
2015	1	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0	0	0	0	0

3.3.2.3 Temporal overlap between Fraser River Sockeye Salmon and VHSV

Fraser River Sockeye Salmon are expected in the Discovery Islands area from mid-May to mid-July for juveniles and June to October for returning adults. Between 2002 and 2019, VHSV has been reported in January, February, April and May of the year through either industry, FHASP or FHE reporting from the industry (Table 10 and Table 11), demonstrating a very limited temporal concurrence (i.e., within one month) between juvenile Fraser River Sockeye Salmon or no temporal overlap between adults and VHSV attributable to Atlantic Salmon farms in the Discovery Islands area.

3.3.2.4 Relative size and volume of Atlantic Salmon farms

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

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

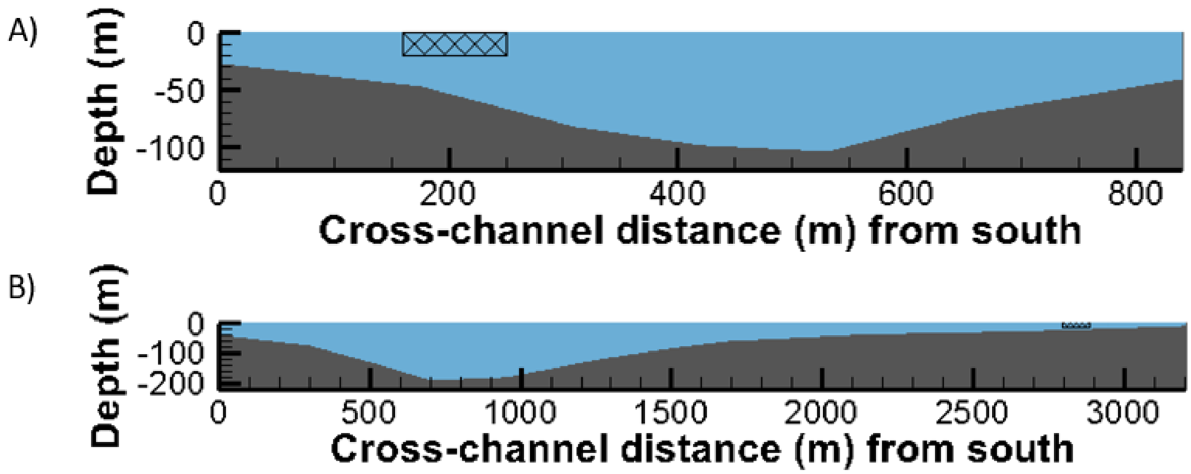

Figure 5. Cross sections of channels at (A) Brent and (B) Shaw farms located in respectively the narrowest and widest channel with Atlantic Salmon farms in the Discovery Islands area. Cross-hatched boxes show the cross-channel projection of the net-pen system of farms depicted at scale, i.e., what fish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

3.3.2.5 Viral haemorrhagic septicaemia virus survival in the marine environment

Laboratory studies have demonstrated that VHSV shed from an infected host can remain infectious in either marine or freshwater environments, yet the duration for which the virus remains infectious is highly dependent upon environmental parameters such as water salinity, temperature, organic load, microbial content, and exposure to ultraviolet light (Garver and Hawley, 2021).

The virus remains infectious longer in freshwater than in seawater with 99.9% of VHSV rendered inactive on average by day four in seawater versus day 13 in freshwater at 15°C (Hawley and Garver, 2008). These viral decay times are contingent upon temperature: trials conducted at 10°C prolonged virus inactivation in seawater and freshwater by three and eight days; respectively, revealing that virus stability is inversely proportional to temperature (Hawley and Garver, 2008). In raw seawater, the time to 99.9% inactivation of VHSV isolates ranged from approximately 10 to 13 days at 4°C and five to 12 days (average of seven days) at 10°C (Hawley and Garver, 2008).

Viral haemorrhagic septicaemia virus is also sensitive to UV light (Øye and Rimstad, 2001) and given its morphological resemblance to IHNV (i.e., enveloped virus) it would be expected that VHSV would display equally rapid inactivation when exposed to sunlight as demonstrated for IHNV (i.e., hours) (Garver et al., 2013a).

3.3.2.6 Oceanographic and environmental conditions

Water temperatures in the Discovery Islands area vary both seasonally and regionally with recorded temperatures ranging between 3°C and 24°C (Chandler et al., 2017). Water salinity in the Discovery Islands area varies considerably by season (depending on river runoff of snowmelt), depth (the estuarine circulation), and location (some narrow channels are extremely well-mixed vertically) ranging from nearly zero to 32 (Chandler et al., 2017).

Monthly distributions of temperature (°C) recorded on active Atlantic Salmon farms in the Discovery Islands area over the last five years (2014-2018) are presented in Figure 6.

Between 2002 and 2018, VHSV occurrences were reported in January to May. All the detections attributed to VHSV were reported in the winter and spring months (Table 10).

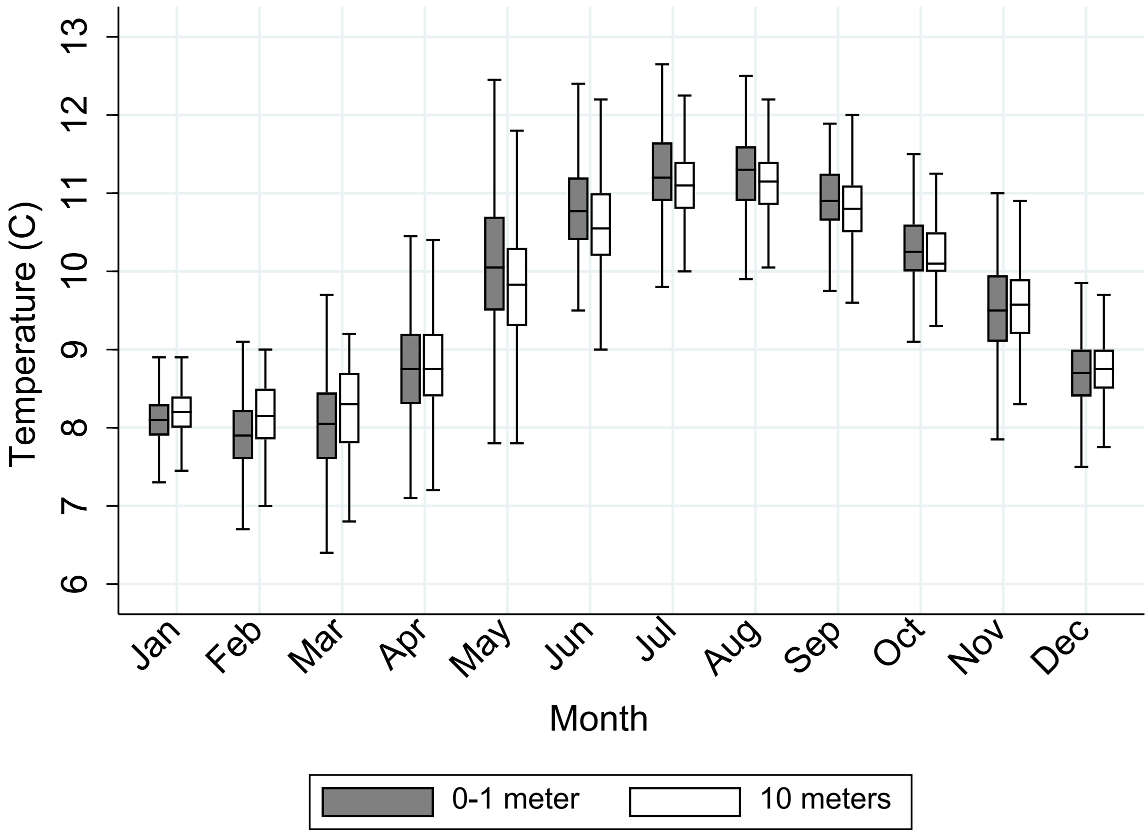

Figure 6. Distribution of temperatures (°C) recorded on active Atlantic Salmon farms in the Discovery Islands area at <1 and 10 meters depth, between 2014 and 2018 (five years). Each box represents the interquartile range (IQR = Q3 – Q1), including the median line. Whiskers indicate the upper (Q3 + (1.5 × IQR)) and lower (Q1 – (1.5 × IQR)) adjacent values. Outliers, defined as values/observations outside the range between upper and lower adjacent values, are not shown for clarity in visualization. Data source: BC Salmon Farmers Association, 2019.

3.3.3 Assumptions

- Viral haemorrhagic septicaemia virus has been released from at least one infected Atlantic Salmon farm in the Discovery Islands area;
- Shedding from infected farmed fish is limited to the month(s) with evidence of infection or disease on farms;
- Fraser River Sockeye Salmon are randomly distributed and present in all channels of the Discovery Islands area; and
- Recognizing the presence of hatchery-produced Sockeye Salmon but given that they cannot be differentiated in the marine environment, wild and hatchery-produced Sockeye Salmon 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 Fraser River Sockeye Salmon to be exposed to VHSV attributable to Atlantic Salmon farm(s) in the Discovery Islands area. These factors were used to determine the likelihood and uncertainty rankings based on the definitions in Table 2, Table 5 and Table 6.

Table 12. Factors contributing to and limiting the likelihood that at least one Fraser River Sockeye Salmon would be exposed to viral haemorrhagic septicaemia virus (VHSV) released from infected Atlantic Salmon farm(s) in the Discovery Islands area under the current farm practices.

Contributing factors	Limiting factors
• Fraser River Sockeye Salmon migrate through the Discovery Islands area every year; • Temporal overlap occurs between juvenile Fraser River Sockeye Salmon and VHS detections on Atlantic Salmon farms in the Discovery Islands area in one month of the year (May); • Under laboratory conditions, VHSV has been shown to be able to survive in seawater for an average of seven days at 10°C; and • Shedding of VHSV from Atlantic Salmon and Pacific Herring has been shown under experimental conditions.	• Temporal overlap does not occur between adult Fraser River Sockeye Salmon and VHSV detections on Atlantic Salmon farms in the Discovery Islands area; • Temporal overlap between juvenile Fraser River Sockeye Salmon and VHS detections does not occur in June and July; • Atlantic Salmon farms are not found in all channels of the Discovery Islands area (Figure 1); • Atlantic Salmon farms occupy a very small surface area and volume of the Discovery Islands area and width of channels; and • Viral haemorrhagic septicaemia virus in water is rendered inactive by environmental factors such as UV light and the natural microbial community.

Two exposure groups were assessed: (1) juvenile Fraser River Sockeye Salmon; and (2) adult Fraser River Sockeye Salmon.

3.3.4.1 Exposure of juvenile Fraser River Sockeye Salmon

It was concluded that the likelihood of at least one juvenile Fraser River Sockeye Salmon to be exposed to VHSV attributable to Atlantic Salmon farms located in the Discovery Islands area through waterborne exposure is **unlikely** under the current farm practices given the limited temporal overlap with VHSV on farms. Of the five years in which VHSV was reported (2002-2019), only one year had evidence of VHSV during the time period that juveniles are present in the Discovery Islands area. This conclusion was made with **reasonable certainty** given abundant and robust data about VHSV occurrences on Atlantic Salmon farms and presence of juvenile Fraser River Sockeye Salmon in the Discovery Islands area but limited knowledge on the spatial distribution of Sockeye Salmon in proximity to farms.

3.3.4.2 Exposure of adult Fraser River Sockeye Salmon

It was concluded that the likelihood of at least one adult Fraser River Sockeye Salmon to be exposed to VHSV attributable to an Atlantic Salmon farm located in the Discovery Islands area through waterborne exposure is **extremely unlikely** under the current farm practices given no temporal overlap with VHSV on the farms. This conclusion was made with **reasonable**

certainty given abundant and robust data about VHSV occurrences on Atlantic Salmon farms and presence of adult Fraser River Sockeye Salmon in the Discovery Islands area but limited knowledge on the spatial distribution of Sockeye Salmon in proximity to farms.

3.4 INFECTION ASSESSMENT

3.4.1 Question

Assuming that Fraser River Sockeye Salmon have been exposed to VHSV released from Atlantic Salmon farms in the Discovery Islands area, what is the likelihood that they are exposed to a concentration and for a period time sufficient to cause infection?

3.4.2 Considerations

Considerations include Sockeye Salmon susceptibility to VHSV infection and duration of exposure of Fraser River Sockeye Salmon to farms.

3.4.2.1 Sockeye Salmon susceptibility to VHSV infection

The World Organisation for Animal Health (OIE) considers a species of aquatic animals to be susceptible to infection with a pathogenic agent when each of the following criteria are met: (1) transmission has been obtained naturally or by experimental procedures that mimic natural pathways for the infection; (2) the identity of the pathogenic agent has been confirmed in accordance with OIE diagnostic criteria or equivalent; and (3) evidence indicates that presence of pathogenic agent constitutes an infection (OIE, 2019).

There is no confirmed detection of VHSV infection in naturally occurring wild Sockeye Salmon across multiple independent surveillance studies, nor have Sockeye Salmon proved susceptible to VHSV infection through experimental cohabitation or immersion studies as summarized in Garver and Hawley (2021). Overall, Sockeye Salmon are not considered susceptible to VHSV based on the OIE criteria described above (OIE, 2019). Note that injection is an invasive experimental procedure that does not mimic natural pathways for disease transmission.

3.4.3 Likelihood of infection

Given that infection is dependent on susceptibility and that Sockeye Salmon are not susceptible to VHSV, it was concluded that a VHSV infection in Sockeye Salmon attributable to Atlantic Salmon farms in the Discovery Islands area is **extremely unlikely** to occur (i.e., has little to no chance to occur, see Table 2). This conclusion was made with **reasonable certainty** given that data from the VHSV challenge trials on Sockeye Salmon are robust.

3.5 OVERALL LIKELIHOOD ASSESSMENT

The estimated likelihoods were combined as per the combination rules described in the methodology section (2.2.5). The combined likelihood for the release assessment was determined by adopting the highest likelihood ranking among the release pathways. The combined likelihood for each exposure group was determined by adopting the lowest ranking among the farm infection, release, exposure and infection assessments.

Table 13 summarizes the likelihood assessment. Overall, it was concluded that the likelihood that Fraser River Sockeye Salmon would become infected with VHSV released from Atlantic Salmon farms in the Discovery Islands area is **extremely unlikely** as Sockeye Salmon are not susceptible to VHSV.

Table 13. Summary of the likelihood and uncertainty rankings for the likelihood assessment of the viral haemorrhagic septicaemia virus (VHSV) risk assessment. Uncertainties are not combined.

Step		Ranking	
Farm infection assessment	**Likelihood (Uncertainty)**	Unlikely (Reasonable Certainty)	
Release assessment	**Release pathways**	**Farmed Atlantic Salmon**	**Mechanical vectors and fomites**
	Likelihood (Uncertainty)	Extremely Likely (High Certainty)	Unlikely (Reasonable Certainty)
	Combined likelihood	Extremely Likely	
Exposure assessment	**Exposure groups**	**Juvenile**	**Adult**
	Likelihood (Uncertainty)	Unlikely (Reasonable Certainty)	Extremely Unlikely (Reasonable Certainty)
Infection assessment	**Likelihood (Uncertainty)**	Extremely Unlikely (Reasonable Certainty)	Extremely Unlikely (Reasonable Certainty)
Overall likelihood for each exposure group (combination of all four steps)		Extremely Unlikely	Extremely Unlikely

4 CONSEQUENCE ASSESSMENT

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

Based on the likelihood assessment, it was determined that it is extremely unlikely that Fraser River Sockeye Salmon would become infected with VHSV released from Atlantic Salmon farms in the Discovery Islands area given Sockeye Salmon are not susceptible to VHSV.

As the consequences are dependent on the susceptibility of Sockeye Salmon, the magnitude of consequences to the abundance and diversity of Fraser River Sockeye Salmon are both estimated as negligible. Fraser River Sockeye Salmon are not susceptible to infection with VHSV. Without infection, there will be no consequence to the abundance (0% reduction in the number of returning Fraser River Sockeye Salmon which is defined as negligible to the consequences to abundance in Table 3) and diversity (no loss of Fraser River Sockeye Salmon which is defined as negligible to the consequences to diversity in Table 4) of Fraser River Sockeye Salmon attributable to VHSV or VHS from Atlantic Salmon farms in the Discovery Islands area.

5 RISK ESTIMATION

5.1 ABUNDANCE

The risk to the abundance of Fraser River Sockeye Salmon due to infections with VHSV attributable to Atlantic Salmon farms in the Discovery Islands area (Table 14) was estimated using the risk matrix combining the results of the likelihood assessment and the results of the consequence assessment to Fraser River Sockeye Salmon abundance (Figure 3).

Table 14. Risk estimation to the abundance of Fraser River Sockeye Salmon resulting from viral haemorrhagic septicaemia virus (VHSV) attributable to Atlantic Salmon farms located in the Discovery Islands area of under current farm practices.

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

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

5.2 DIVERSITY

The risk to the diversity of Fraser River Sockeye Salmon due to infections with VHSV attributable to Atlantic Salmon farms in the Discovery Islands area (Table 15) was estimated using the risk matrix combining the results of the likelihood assessment and the results of the consequence assessment to Fraser River Sockeye Salmon diversity (Figure 4).

Table 15. Risk estimation to the diversity of Fraser River Sockeye Salmon resulting from viral haemorrhagic septicaemia virus (VHSV) attributable to Atlantic Salmon farms located in the Discovery Islands area of under current farm practices.

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

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

6 UNCERTAINTY ANALYSIS

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

The main sources of uncertainties, the approach taken to address each of them, and their potential impacts on the results/rankings in this risk assessment are listed in Table 16. As presented in the table, we evaluated each potential source of uncertainty and took it into consideration in our final analysis. We applied different tools/methods available, including making relevant assumptions, using surrogate information, considering worst-case scenario, and sensitivity analysis. Finally, the expected direction and magnitude of each action in addressing the respective source of uncertainty is presented.

For instance, in the exposure assessment step, one of the major sources of uncertainty is "knowledge gaps around the precise migration routes and movements of fish through the channels of the Discovery Islands area." To account for this uncertainty in the ranking of the likelihood of exposure, we assumed that the fish had random distribution and movement throughout all channels of the Discovery Islands area in each month during their migration window. Therefore, every fish was considered to have a chance to become exposed to infected farm(s). In other words, we highly overestimated the likelihood of exposure for the migratory populations because, in reality, we expect that different populations of Sockeye Salmon (especially, juveniles) use specific pathways/channels along their migration routes and may not meet an infected farm; thus, they are expected to have substantially lower likelihood of exposure than what we conservatively estimated. For a better understanding of the potential impact of this assumption on the ranking of the likelihood of exposure, please revisit Section 3.3.2.4.

Table 16. Main sources of uncertainty, considerations used to address them, and potential impacts on the likelihood rankings and the final conclusions of this risk assessment. Impact on assessment ranking' represents the potential impacts of our action to address that specific source of uncertainty. 'Impact on final risk' represents the potential impact of the uncertainty and our respective action on changing the final category of the risk (green, yellow, or red). FHASP: Fish Health Audit and Surveillance Program. VHS: viral haemorrhagic septicaemia. VHSV: viral haemorrhagic septicaemia virus.

Assessment step (Uncertainty ranking)	Main source of uncertainty	Considerations used to account for this uncertainty	Impact on assessment ranking	Impact on final risk estimate
Farm infection assessment **(reasonable certainty)**	Are all occurrences of VHS and VHSV infection on farms detected?	Data collection and confirmation from industry and regulatory authorities. Detection of virus in a single fish is assumed to be equivalent evidence of infection at a farm-level.	Could increase or decrease the likelihood ranking	None because of combination rules – there are other likelihoods both higher and lower that would be carried forward and because the infection assessment determined the overall likelihood.
Release assessment: Vectors and Fomites **(reasonable certainty)**	Are disinfection protocols specific to VHSV efficacious and are biocontainment protocols consistently implemented?	Characterize the audit deficiency rates as an evaluation of daily practices. One detection indicating no evidence of farm-to-farm transmission in the farm infection data suggests that fish health management practices are effective.	Could increase or decrease the likelihood ranking	None because the higher ranking of release from infected Atlantic Salmon determines this release step.
Exposure assessment **(reasonable certainty)**	How well do we understand proximity of Fraser River Sockeye Salmon to salmon farms during their migration through the Discovery Islands area?	Assume that as a population, Sockeye Salmon can use all channels and that they therefore have a chance to be exposed to an Atlantic Salmon farm with VHSV infection.	Could increase the likelihood ranking	None because the infection assessment determined the overall likelihood.
Infection assessment **(reasonable certainty)**	Have laboratory challenge studies examined the full range of factors that wild Sockeye Salmon can experience in the environment around salmon farms??	Assume that laboratory studies are applicable as similar studies reach similar conclusions.	Could increase the likelihood ranking	Would need to do consequence assessment if Sockeye Salmon were susceptible to determine impact on risk.

7 CONCLUSIONS

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

The conclusion of minimal risk was mainly influenced by the absence of VHSV infection in Sockeye Salmon as the available data indicate Sockeye Salmon do not fulfill the OIE criteria for susceptibility and is therefore not a susceptible species.

However, if a genotype/subgenotype of VHSV other than IVa were to be reported on Atlantic Salmon farms in the Discovery Islands area, a specific risk assessment on that genotype may need to be undertaken. If Sockeye Salmon were found to be susceptible to VHSV-IVa, this risk assessment would have to be redone.

8 REFERENCES CITED

Bovo, G., Hill, B., Husby, A., Håstein, T., Michel, C., Olesen, N. J., Storset, A. and Midtlyng, P. J. 2005. Work package 3 report: Pathogen survival outside the host, and susceptibility to disinfection. Health 6: 1244-1249.

Bowker, J., Trushenski, J., Tuttle-Lau, M., Straus, D., Gaikowski, M., Goodwin, A., Sprague, L. and Bowman, M. 2019. Guide to using drugs, biologics, and other chemicals in aquaculture. Bethesda, Maryland. American Fisheries Society Fish Culture Section. 78 p.

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. 2012. 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.

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

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

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

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

DFO. 2020a. Fish health events at British Columbia marine finfish aquaculture sites. Fisheries and Oceans Canada.

DFO. 2020b. Mortality events at British Columbia marine finfish aquaculture sites. Fisheries and Oceans Canada.

DFO. 2020c. Results of DFO fish health audits of British Columbian marine finfish aquaculture sites, by facility. Fisheries and Oceans Canada.

Einer-Jensen, K., Ahrens, P., Forsberg, R. and Lorenzen, N. 2004. Evolution of the fish rhabdovirus viral haemorrhagic septicaemia virus. J. Gen. Virol. 85: 1167-1179.

Elsayed, E., Faisal, M., Thomas, M., Whelan, G., Batts, W. N. and Winton, J. R. 2006. Isolation of viral haemorrhagic septicaemia virus from muskellunge, *Esox masquinongy* (Mitchill), in Lake St Clair, Michigan, USA reveals a new sublineage of the North American genotype. J. Fish Dis. 29(10): 611-619.

Faisal, M. and Schulz, C. A. 2009. Detection of viral hemorrhagic septicemia virus (VHSV) from the leech *Myzobdella lugubris* Leidy, 1851. Parasite. Vector. 2(1): 45.

Faisal, M. and Winters, A. D. 2011. Detection of viral hemorrhagic septicemia virus (VHSV) from *Diporeia* spp. (Pontoporeiidae, Amphipoda) in the Laurentian Great Lakes, USA. Parasite. Vector. 4: 2.

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.

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.

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

Garver, K. A. and Hawley, L. M. 2021. Characterization of Viral Haemorrhagic Septicaemia Virus (VHSV) to inform pathogen transfer risk assessments in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/064. v + 24 p.

Garver, K. A., Mahony, A. A. M., Stucchi, D., Richard, J., Van Woensel, C. and Foreman, M. 2013a. Estimation of parameters influencing waterborne transmission of infectious hematopoietic necrosis virus (IHNV) in Atlantic Salmon (*Salmo salar*). PLoS One 8(12): e82296.

Garver, K. A., Traxler, G. S., Hawley, L. M., Richard, J., Ross, J. P. and Lovy, J. 2013b. Molecular epidemiology of viral haemorrhagic septicaemia virus (VHSV) in British Columbia, Canada, reveals transmission from wild to farmed fish. Dis. Aquat. Org. 104(2): 93-104.

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

Getchell, R. G., Cornwell, E. R., Groocock, G. H., Wong, P. T., Coffee, L. L., Wooster, G. A. and Bowser, P. R. 2013. Experimental transmission of VHSV genotype IVb by predation. J. Aquat. Anim. Health 25(4): 221-229.

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.

Guðmundsdóttir, S., Vendramin, N., Cuenca, A., Sigurðardóttir, H., Kristmundsson, A., Iburg, T. M. and Olesen, N. J. 2019. Outbreak of viral haemorrhagic septicaemia (VHS) in lumpfish (*Cyclopterus lumpus*) in Iceland caused by VHS virus genotype IV. J. Fish Dis. 42(1): 47-62.

Hawley, L. M. and Garver, K. A. 2008. Stability of viral hemorrhagic septicemia virus (VHSV) in freshwater and seawater at various temperatures. Dis. Aquat. Org. 82(3): 171-178.

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.

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

Kocan, R. M., Bradley, M., Elder, N., Meyers, T., Batts, W. N. and Winton, J. R. 1997. North American strain of viral hemorrhagic septicemia virus is highly pathogenic for laboratory-reared Pacific herring. J. Aquat. Anim. Health 9(4): 279-290.

Lovy, J., Lewis, N. L., Hershberger, P. K., Bennett, W., Meyers, T. R. and Garver, K. A. 2012. Viral tropism and pathology associated with viral hemorrhagic septicemia in larval and juvenile Pacific herring. Vet. Microbiol. 161(1-2): 66-76.

Lovy, J., Piesik, P., Hershberger, P. K. and Garver, K. A. 2013. Experimental infection studies demonstrating Atlantic salmon as a host and reservoir of viral hemorrhagic septicemia virus type IVa with insights into pathology and host immunity. Vet. Microbiol. 166: 91-101.

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.

Marty, G. D., Freiberg, E. F., Meyers, T. R., Wilcock, J., Farver, T. B. and Hinton, D. E. 1998. Viral hemorrhagic septicemia virus, *Ichthyophonus hoferi*, and other causes of morbidity in Pacific herring *Clupea pallasii* spawning in Prince William Sound, Alaska, USA. Dis. Aquat. Org. 32: 15-40.

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. 2020a. 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., Jones, S. R. M., Wade, J., Aubry, P., Johnson, S., Foreman, M. G. G., Garver, K. A., Holt, C., Boily, F., Burgetz, I. J. and Parsons, G. J. 2020b. Assessment of the risk to Fraser River Sockeye Salmon due to *Piscirickettsia salmonis* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/021. ix + 56 p.

Mimeault, C., Nekouei, O., Garver, K. A., Jones, S. R. M., Johnson, S., Holt, K., Aubry, P., Weber, L., Burgetz, I. J. and Parsons, G. J. 2020c. Assessment of the risk to Fraser River Sockeye Salmon due to *Moritella viscosa* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/058. vii + 30 p.

Mimeault, C., Nekouei, O., Garver, K.A., Jones, S.R.M., Johnson, S., Holt, K., Aubry, P., Weber, L., Burgetz, I.J. and Parsons, G.J. 2020. Assessment of the risk to Fraser River Sockeye Salmon due to *Tenacibaculum maritimum* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/059. viii + 49 p.

Mimeault, C., Polinski, M., Garver, K. A., Jones, S. R. M., Johnson, S., Boily, F., Malcolm, G., Holt, K., Burgetz, I. J. and Parsons, G. J. 2019. Assessment of the risk to Fraser River Sockeye Salmon due to piscine orthoreovirus (PRV) transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/036. viii + 45 p.

Mimeault, C., Wade, J., Boily, F., Johnson, S., Jones, S. R. M., Aubry, P., Foreman, M. G. G., Garver, K. A., Holt, C., Burgetz, I. J. and Parsons, G. J. 2020e. Assessment of the risk to Fraser River Sockeye Salmon due to *Yersinia ruckeri* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/023. viii + 44 p.

Mimeault, C., Wade, J., Boily, F., Johnson, S., Jones, S. R. M., Aubry, P., Malcolm, G., Foreman, M. G. G., Chandler, P. C., Wan, D., Garver, K. A., Holt, C., Burgetz, I. J. and Parsons, G. J. 2020f. Assessment of the risk to Fraser River Sockeye Salmon due to *Renibacterium salmoninarum* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/019. ix + 63 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.

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.

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.

OIE. 2016. OIE-Listed diseases, infections and infestations in force in 2016.

OIE. 2019. Criteria for listing species as susceptible to infecion with a specifc pathogen. Aquatic Animal Health Code. p. 1-4.

Øye, A. K. and Rimstad, E. 2001. Inactivation of infectious salmon anaemia virus, viral haemorrhagic septicaemia virus and infectious pancreatic necrosis virus in water using UVC irradiation. Dis. Aquat. Org. 48(1): 1-5.

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

Pham, P. H., Jung, J., Lumsden, J. S., Dixon, B. and Bols, N. C. 2012. The potential of waste items in aquatic environments to act as fomites for viral haemorrhagic septicaemia virus. J. Fish Dis. 35(1): 73-77.

Schönherz, A. A., Hansen, M. H., Jørgensen, H. B. H., Berg, P., Lorenzen, N. and Einer-Jensen, K. 2012. Oral transmission as a route of infection for viral haemorrhagic septicaemia virus in rainbow trout, *Oncorhynchus mykiss* (Walbaum). J. Fish Dis. 35(6): 395-406.

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.

9 APPENDIX

9.1 INDUSTRY SURVEILLANCE AND DETECTIONS

Table 17 provides a summary of industry's data by fish health staff made during site visits and samplings for VHSV molecular 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.

All laboratory tests targeting VHSV (PCRs and virology) were tallied to report the total number of site visits testing for VHSV. All results indicating a positive for VHSV were counted as evidence.

The industry detected the presence of VHSV in Atlantic Salmon farms located in the Discovery Islands area in 2012 and 2014-2015.

Table 17. Viral haemorrhagic septicaemia virus (VHSV) detections between 2011 and 2019 summarized from data provided by the three companies rearing Atlantic Salmon in marine sites located in the Discovery Islands area. Data include polymerase chain reaction and virology test results for VHSV during a site visit.

Year	Number of site visits with evidence of VHSV / total number of site visits with testing for VHSV	Number of farms with evidence of VHSV / total number of farms with fish health visits and testing for VHSV
2011	0 / 20	0 / 11
2012	1 / 35	1 / 9
2013	0 / 6	0 / 6
2014	1 / 22	1 / 6
2015	1 / 17	1 / 7
2016	0 / 43	0 / 11
2017	0 / 46	0 / 11
2018	0 / 37	0 / 9
2019	0 / 16	0 / 10