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

National Capital Region

Canadian Science Advisory Secretariat
Science Advisory Report 2019/017

ADVICE FROM THE 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

Net-pen along the coast of British Columbia (photo credit: DFO).

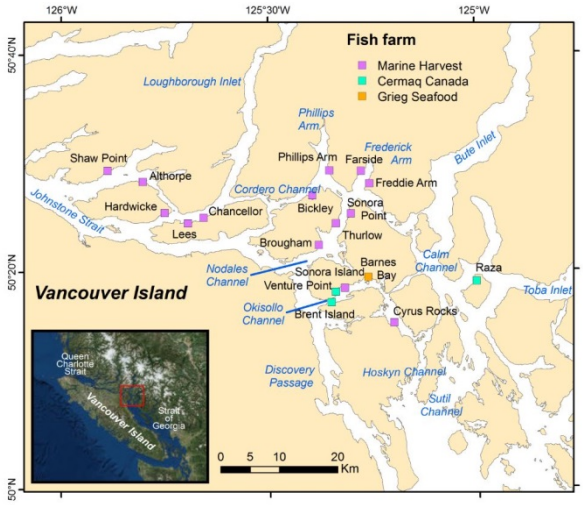

Figure 1. Locations of the 18 Atlantic Salmon farms in the Discovery Islands area stocked at least once between 2010 and 2016.

Context:

Fisheries and Oceans Canada (DFO), under the Sustainable Aquaculture Program, is committed to deliver environmental risk assessments to support science-based decision making related to aquaculture activities. The Aquaculture Science Environmental Risk Assessment Initiative was implemented to assess the risks of aquaculture activities to wild fish and the environment. The risks associated with each environmental stressor validated in the Pathways of Effects for finfish and shellfish aquaculture (DFO, 2010) will be assessed as per the Aquaculture Science Environmental Risk Assessment Framework ensuring a systematic, consistent and transparent process.

DFO's Aquaculture Management Directorate has requested CSAS advice on the risks to Fraser River Sockeye Salmon due to pathogen transfer from marine Atlantic Salmon farms located in the Discovery Islands area in British Columbia. This request supports DFO's role in the management of aquaculture in British Columbia and aligns with recommendations in the final report of the Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River, including recommendations 18 and 19 on risks to wild fish populations related to pathogen transfer from finfish farms (Cohen, 2012).

The advice is provided through a series of pathogen transfer risk assessments, this second series focusing on Aeromonas salmonicida (the causative agent of furunculosis), Piscirickettsia salmonis (the causative agent of salmonid rickettsial septicaemia (SRS)), Renibacterium salmoninarum (the causative

agent of bacterial kidney disease (BKD)) and Yersinia ruckeri (the causative agent of enteric redmouth disease (ERM)), respectively. These bacterial pathogens are known to cause disease and have been reported by the industry and/or have been diagnosed through the DFO Fish Health Audit and Surveillance Program on Atlantic Salmon farms in the Discovery Islands area. The risks associated with other pathogens also known to cause disease on marine Atlantic Salmon farms in the Discovery Islands area will be assessed in subsequent processes.

This Science Advisory Report is from the November 6–8, 2018 national advisory meeting on Assessment of the risk to Fraser River sockeye salmon due to bacteria causing systemic infections transferred from Atlantic salmon farms located in the Discovery Islands area, British Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

Aeromonas salmonicida transfer risk assessment

- The assessment was conducted using farm-related and environmental data from 2002–2017, based on the current fish health management practices, and considering relevant scientific information.
- The assessment concluded that *A. salmonicida* attributable to Atlantic Salmon (*Salmo salar*) farms operating in the Discovery Islands area poses minimal risk to Fraser River Sockeye Salmon (*Oncorhynchus nerka*) abundance and diversity. During this assessment uncertainties were evaluated at each step and ranged from high certainty to reasonable uncertainty (see bullets below and Table 1).
- Two main factors influenced the attribution of minimal risk:
    - in the likelihood assessment, it was determined that it is very unlikely that Fraser River Sockeye Salmon would become infected with *A. salmonicida* released from an Atlantic Salmon farm in the Discovery Islands area. The uncertainties for the different likelihood steps ranged from high certainty to reasonable uncertainty; and
    - in the consequences steps, it was determined in the very unlikely event that Fraser River Sockeye Salmon would become infected with *A. salmonicida* due to Atlantic Salmon farms in the Discovery Islands area, the infection would not be expected to spread within wild populations, hence the magnitude of consequences to both Fraser River Sockeye Salmon abundance and diversity would be negligible with reasonable uncertainty.
- The overall likelihood assessment, including separate farm infection, release, exposure, and infection assessments, was supported by the following key findings:
    - evidence of *A. salmonicida* and/or furunculosis on Atlantic Salmon farms in the Discovery Islands area;
    - the temporal overlap of migrating juvenile and adult Fraser River Sockeye Salmon with reports of *A. salmonicida* on Atlantic Salmon farms in the Discovery Islands area;
    - infected Atlantic Salmon shed *A. salmonicida* into the surrounding environment at all stages of infection and after death;
    - the estimated maximum *A. salmonicida* waterborne concentration on farms or dispersed from farms is not expected to cause infection in migrating Sockeye Salmon; and
    - an infection with *A. salmonicida* attributable to Atlantic Salmon farms, would not be expected to spread within Fraser River Sockeye Salmon.
- Uncertainty: Certainty in this assessment is limited by the lack of knowledge about:

- how long and how close populations of wild juvenile and adult Pacific salmon are in the vicinity of Atlantic Salmon farms;
- the minimum infectious dose of *A. salmonicida* for Sockeye Salmon and other Pacific salmon species;
- furunculosis-related mortality in susceptible Pacific salmon;
- the spread of infection within migrating populations of Pacific salmon; and
- the consequences to abundance and diversity of Fraser River Sockeye Salmon resulting from sub-lethal effects of *A. salmonicida* infection.

- For the purpose of the assessment, a number of key assumptions were made:
  - positive detection of the pathogen on an Atlantic Salmon farm in the Discovery Islands area is evidence of *A. salmonicida* infection on that farm;
  - Atlantic Salmon and Sockeye Salmon are equally susceptible to *A. salmonicida* infections and furunculosis; and
  - current management practices are followed and will be maintained, including vaccination of 100% of farmed Atlantic Salmon to prevent furunculosis, surveillance for early detection and biosecurity measures.

Additionally, this risk assessment was informed by a summary of the current state of knowledge related to *A. salmonicida* and furunculosis (Boily et al., 2019) of which the most relevant elements are summarized below.

Characterization of *Aeromonas salmonicida* and furunculosis

- Infection with *A. salmonicida* can lead to the development of furunculosis, a septicemic bacterial disease, in salmonid fishes in freshwater, brackish and marine environments.
- Information about interspecific and intraspecific variability in susceptibility is limited; however, all salmonid species are considered susceptible to *A. salmonicida* infection and disease.
- Infection with *A. salmonicida* and the development of disease can occur in all life stages of fish; however, there are insufficient data to assign different susceptibilities to different life history stages of Pacific salmon.
- *A. salmonicida* is transmitted horizontally, therefore, susceptible fish can become infected through contact with: infected fish, contaminated water and/or contaminated equipment.
- The bacterium is shed at all stages of infection including dead hosts. Shedding rates have been reported in Atlantic Salmon in seawater.
- The survival of *A. salmonicida* in raw seawater varies from 2 to 26 days and is dependent upon physical conditions including temperature, salinity and visible and ultraviolet radiation.
- Minimum infectious or lethal doses of *A. salmonicida* in Sockeye Salmon could not be found in the literature.

INTRODUCTION

This risk assessment was conducted under the DFO Aquaculture Science Environmental Risk Assessment Initiative, implemented as a structured approach to provide risk-based science advice to further support sustainable aquaculture in Canada. Risk assessments conducted under this initiative follow the Aquaculture Science Environmental Risk Assessment Framework

which is consistent with international and national risk assessment frameworks (GESAMP, 2008; ISO, 2009). Details about the initiative and the framework are available on the DFO Aquaculture Science Environmental Risk Assessment Initiative webpage. All risk assessments conducted under the Initiative do not include socio-economic considerations.

This advisory report is one of four summarizing the consensus advice developed during the November 6–8, 2018 Canadian Science Advisory Secretariat (CSAS) scientific peer-review meeting that included international and national scientific experts. The information and current scientific knowledge about *A. salmonicida* and furunculosis and the draft risk assessment were presented in the following documents:

- Characterization of *Aeromonas salmonicida* and furunculosis to inform pathogen transfer risk assessments in British Columbia (Boily et al., 2019);
- Assessment of the risk to Fraser River Sockeye Salmon due to *Aeromonas salmonicida* on Atlantic Salmon farms in the Discovery Islands area, British Columbia (Mimeault et al., 2019).

The two supporting research documents were reviewed and used to address the following objectives of the meeting, specifically:

- review the qualitative assessments of the risk to Fraser River Sockeye Salmon abundance and diversity due to *A. salmonicida* transferred from Atlantic Salmon farms located in the Discovery Islands area;
- review and assess the uncertainties associated with the estimation of the risk to Fraser River Sockeye Salmon abundance and diversity; and
- if risk assessment outcomes warrant, provide advice on additional measures that would reduce the risk to Fraser River Sockeye Salmon abundance and diversity due *A. salmonicida* transferred from Atlantic Salmon farms in the Discovery Islands area.

ANALYSIS

Characterization of *Aeromonas salmonicida* and furunculosis

Aeromonas salmonicida is an endemic bacterial pathogen in Canada, causing furunculosis, a septicemic bacterial disease found primarily in salmonid fishes. Infection may be transient or cause disease, depending on the host, pathogen virulence and environmental conditions. Covert infections with *A. salmonicida* are clinically unapparent and can persist until stress induces clinical furunculosis (Hiney and Olivier, 1999). Carrier states may be established in fish that have survived infection (McCarthy and Roberts, 1980; Austin and Austin, 2016) or in fish already infected with *A*. *salmonicida* that are subsequently vaccinated against this bacterium (Hiney, 1995).

All salmonid species are considered susceptible to *A. salmonicida* infection and furunculosis (Kent, 2011); however, interspecific and intraspecific variability in susceptibility within and across salmonid species is largely unknown; however, Rainbow Trout is more resistant than other salmonids Furthermore, there are insufficient data to assign different susceptibilities to different life history stages of salmonids.

Aeromonas salmonicida is shed from fish during most stages of infection and from dead hosts via urine, faeces and ruptured furuncles. Shedding rates have been estimated under laboratory conditions in both *A. salmonicida*-infected Atlantic Salmon (Rose et al., 1989) and Rainbow

Trout (*O. mykiss*) (McCarthy, 1977; Pérez et al., 1996). Peak shedding rates (range: 9.0×10^6 to 6.4×10^8 colony forming units (cfu) per fish per hour) in saltwater were reported in 1200 g Atlantic Salmon on the day of death under laboratory conditions (Rose et al., 1989). Shedding rates in healthy carriers have not been reported.

While there are no published studies on the infectious or minimum lethal dose of *A. salmonicida* specific to Sockeye Salmon, using data from one freshwater bath challenge study with Sockeye Salmon fry (5.7 g fish, n=21), the minimum lethal dose following a short exposure duration (≤20 minutes) is $<1 \times 10^4$ cfu/mL (McCarthy, 1983). The lowest dose of *A. salmonicida* to have caused mortality in salmonids in a challenge study was reported in Atlantic Salmon (75 to 115 g, n=10) exposed to 1×10^8 cfu/m^3 (10^2 *A. salmonicida* cfu/mL) in seawater for 12 hours a day for 21 days, which resulted in 20% mortality; however, exposure for seven days did not result in mortality or infection (Rose et al., 1989).

The primary mode of *A. salmonicida* transmission is horizontal within and among wild and farmed salmon populations.

Survival of *A. salmonicida* in the marine environment is influenced by the presence of particulate matter as well as physical conditions, e.g., temperature, salinity and visible and ultraviolet radiation). Based on laboratory studies, survival in raw seawater can range from 2 to 26 days (McCarthy, 1977; Rose, 1990). *A salmonicida* can also survive for a prolonged period of time attached to a variety of substrates such as wood and sediment in the marine environment (Effendi and Austin, 1994).

Occurrence on Atlantic Salmon farms in BC

Data on the occurrence of *A. salmonicida* and furunculosis on Atlantic Salmon farms in BC were obtained from Fish Health Events (FHE), Fish Health Audit and Surveillance Program (FHASP) and mortality events reports. See Wade (2017) for further details regarding these sources of data. Supplementary industry data on fish health and environmental parameters was also included in the analysis.

Between 2002 and the end of 2017, a total of 61 FHEs attributed to furunculosis were reported on Atlantic Salmon farms in BC.

Farm-level diagnoses of furunculosis in BC Atlantic Salmon farms were made in five of 15 BC provincial audits from 2002 to 2016). There was a total of 11 farm-level diagnoses of furunculosis in BC, none of which occurred in the Discovery Islands area.

Aeromonas salmonicida transfer risk assessment

Mimeault et al. (2019) provide the complete assessment of the risk to Fraser River Sockeye Salmon abundance and diversity due to *A. salmonicida* transferred from Atlantic Salmon farms in the Discovery Islands area of British Columbia. The risks were assessed using fish health data and environmental conditions from 2002–2017 and applying current fish health management practices. The elements most relevant to inform the *A. salmonicida* transfer risk assessment are summarized here.

Current fish health management practices include regulatory requirements (e.g., Salmonid Health Management Plan (SHMP) and accompanying proprietary Standard Operating Procedures (SOPs) and, regulation of movement of live fish) and additional voluntary industry practices (e.g., additional surveillance and testing, and vaccination to prevent furunculosis). A commercially available vaccine is used on Atlantic Salmon farms in BC to prevent

furunculosis in salmonids. Although there is no publicly available efficacy for the vaccine, it is considered to be efficacious by companies operating in the Discovery Islands area (Boily et al., 2019). However, despite 100% vaccine coverage of Atlantic Salmon in hatcheries, furunculosis may still develop under stress conditions (i.e., handling, transfer between sites, environmental stress, etc.) if carriers were already present in the population prior to vaccination, or if the vaccine is not fully effective against a strain of *A. salmonicida.*

Conceptual model

The risk assessment followed three main steps outlined in Figure 2, which included the likelihood assessment, consequence assessment and estimation of risk.

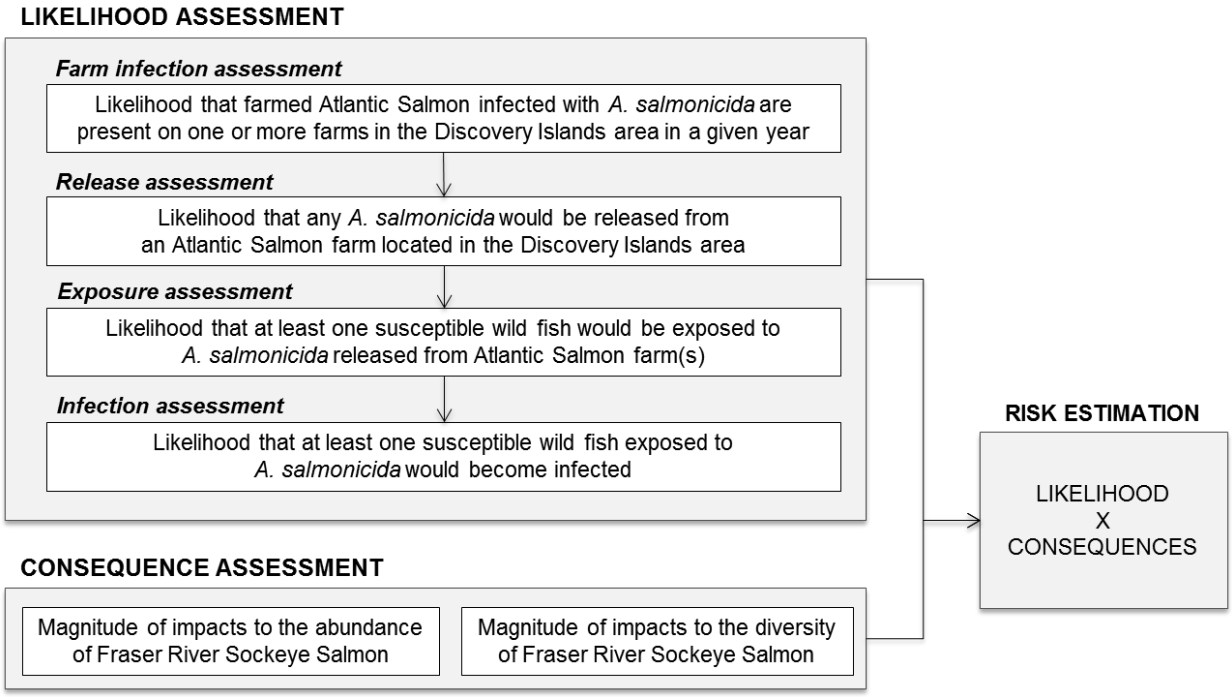

Figure 2. Conceptual model for risk assessment of Aeromonas salmonicida *transfer from Atlantic Salmon farms located in the Discovery Islands area, BC.*

Likelihood assessment

The likelihood assessment was conducted through four sequential steps: farm infection, release, exposure and infection assessments. Each step of the likelihood assessment assumes that current management practices on Atlantic Salmon farms are followed and will be maintained. The main considerations and conclusions are reported here.

Farm infection assessment

Results from industry surveillance and screening (2011–2017), regulatory FHE and mortality events reporting and the Fish Health Audit and Surveillance Program (2002–2017) demonstrate that there is evidence of *A. salmonicida* and/or furunculosis on a total of seven Atlantic Salmon farms in the Discovery Islands area in six different years (2003, 2009, 2010, 2013, 2014 and 2017).

Given evidence of *A. salmonicida* and/or furunculosis in six of sixteen years, it was concluded with reasonable certainty that the likelihood that farmed Atlantic Salmon infected with *A. salmonicida* could be present on one or more Atlantic Salmon farms in the Discovery Islands area is unlikely under the current fish health management practices.

Release assessment

Notwithstanding the likelihood from the farm infection assessment, the release assessment determined the likelihood that any *A. salmonicida* would be released from an infected Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to wild fish populations. Two potential release pathways were considered: release through infected farmed Atlantic Salmon and, release through mechanical vectors (e.g., personnel, visitors and wildlife) and fomites (e.g., farm equipment and vessels).

As Atlantic Salmon are reared in net pens and infected Atlantic Salmon can shed *A. salmonicida* into the surrounding environment, it was concluded with high certainty that the likelihood of release into the environment from infected Atlantic Salmon is extremely likely.

As relevant biosecurity practices are part of licence requirements and specified in farm SHMPs and associated SOPs and the low levels of operational deficiencies related to fish health on Atlantic Salmon farms in the Discovery Islands area, it was concluded with reasonable certainty that the likelihood of release through vectors or fomites is unlikely under current fish health management practices.

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

Exposure assessment

The exposure assessment determined the likelihood that at least one susceptible fish would be exposed to *A. salmonicida* in a given year, assuming that *A. salmonicida* has been released from at least one Atlantic Salmon farm in the Discovery Islands area.

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

The exposure assessment examined whether *A. salmonicida* infections on farms occurred during the same period of time that Pacific salmon are known to be in the Discovery Islands area.

Aeromonas salmonicida has been reported on at least one Atlantic Salmon farm in the Discovery Islands area in all months except March, July, November and December. Evidence of infection has been reported on at most one farm in any given month.

Juvenile lake-type Fraser River Sockeye Salmon migrate through the Discovery Islands area from approximately mid-May to mid-July, whereas returning adults migrate through from approximately late-June to early-October (reviewed in Grant et al. (2018)). To account for annual variations in migration timing, it was assumed that juveniles could be present in the Discovery Islands area from the beginning of May through the end of July. Similarly, for returning adults, it was assumed that adult Sockeye Salmon could be present in the Discovery Islands area from the beginning on June through to the end of October. Other Pacific salmon species can be found in the Discovery Islands area from mid-March to October with Chinook

Salmon (*O. tshawytscha*) potentially found in the area all year-round (Zetterberg and Carter, 2010; Zetterberg et al., 2012) . Consequently, there is potential for temporal overlap between *A. salmonicida* released from infected Atlantic Salmon farms and all exposure groups in the Discovery Islands area.

Out of the six years in which evidence of *A. salmonicida* and/or furunculosis has been recorded on farms since 2002, three years reported evidence during the months when juvenile and adult Fraser River Sockeye Salmon are expected to be present in the Discovery Islands area. Therefore, it was concluded with reasonable certainty that exposure of at least one juvenile or adult Fraser River Sockeye Salmon to *A. salmonicida* released from Atlantic Salmon farm(s) in the Discovery Islands area is likely.

As there is less known about the migration and residency patterns of other Pacific salmon species through the Discovery Islands area, it was concluded with reasonable uncertainty that it is extremely likely for at least one fish (susceptible Pacific salmon species) other than Fraser River Sockeye Salmon to be exposed to *A. salmonicida* released from Atlantic Salmon farm(s) located in the Discovery Islands area.

Infection assessment

The infection assessment determined the likelihood that at least one susceptible wild fish would become infected, assuming at least one susceptible wild fish has been exposed to *A. salmonicida* released from Atlantic Salmon farm(s) operating in the Discovery Islands area. To do so, the *A. salmonicida* waterborne concentration attributable to Atlantic Salmon farms was estimated (see below) and compared to concentrations required to cause infection in fish.

The duration of exposure from Atlantic Salmon farms is not precisely known. A recent telemetry study (Rechisky et al., 2018) reported observations with tagged Sockeye Salmon suggesting transient interactions with farm infrastructure. Further, Mimeault et al. (2017) used information about migration timing, estimates of migration speed and distance, to estimate that juvenile Fraser River Sockeye Salmon could encounter Atlantic Salmon farms over three to eight days during their migration through the Discovery Islands area.

Estimates of the concentration of *A. salmonicida* shed from infected farmed Atlantic Salmon were calculated using laboratory-derived *A. salmonicida* shedding rates for 1200 g Atlantic Salmon (5.4×10^7 cfu per fish per hour as per Rose et al. (1989)), the slowest estimated decay rate (0.66/day as per (Boily et al., 2019)), mortality-derived estimates of infection prevalence within the farmed stock and average farm size.

The within farm maximum *A. salmonicida* waterborne concentration, was calculated to be 1.1×10^7 cfu/m^3 without hydrodynamic dispersal. This estimated concentration is approximately two orders of magnitude lower than the laboratory-derived lethal dose for Sockeye Salmon fry (in freshwater) and nine times lower than the concentration documented to not cause infection in Atlantic Salmon (10^8 cfu/m^3) after daily 12-h exposure for seven days.

Further, hydrodynamic modeling and predictions of the dispersal and estimated concentrations of *A. salmonicida* in the channels within the Discovery Islands area were completed, assuming all 18 farms are infected. The estimated highest concentration of *A. salmonicida* (1.5×10^6 cfu/m^3) was almost two orders of magnitude lower than the concentration that did not cause infection in Atlantic Salmon (10^8 cfu/m^3 from 12-hr bath exposure for seven days as per Rose et al. (1989)), and four orders of magnitude lower than the lowest documented lethal concentration (10^{10} cfu/m^3, 20 min bath exposure) for Sockeye Salmon.

As waterborne concentrations of *A. salmonicida* were calculated using models and comparisons to lethal doses for Sockeye Salmon fry in freshwater laboratory studies, it was concluded with reasonable uncertainty that it is very unlikely that the waterborne concentration of *A. salmonicida* from infected Atlantic salmon farm(s) in the Discovery Islands area, and the duration of exposure would be sufficient to infect at least one Pacific salmon, including juvenile and adult Fraser River Sockeye Salmon.

Overall likelihood assessment

Table 1 summarizes the likelihood assessment. It was concluded that the likelihood that Fraser River Sockeye Salmon and other *A. salmonicida* susceptible Pacific salmon species would become infected with *A. salmonicida* attributable to Atlantic Salmon farms located in the Discovery Islands area is very unlikely for all exposure groups.

Uncertainties for each step in the likelihood assessment are not combined but are rather reported separately for clarity and transparency.

Table 1. Summary of the likelihood and uncertainty rankings for the likelihood assessment of the Aeromonas salmonicida *risk assessment. Estimates are reported in white cells and likelihood combination results are reported in shadowed cells under the "Rankings" column.*

Steps		**Rankings**		
Farm infection assessment	**Likelihood of farm infection**	Unlikely *(reasonable certainty)*		
Release assessment	**Release pathways**	**Farmed Atlantic Salmon**	**Mechanical vectors and fomites**	
	Likelihood of release	Extremely likely *(high certainty)*	Unlikely *(reasonable certainty)*	
	Combined likelihoods of release	Extremely likely		
Exposure and infection assessments	**Exposure groups**	**Juvenile Fraser River Sockeye Salmon**	**Adult Fraser River Sockeye Salmon**	**Other Pacific salmon species**
	Likelihood of exposure	Likely *(reasonable certainty)*	Likely *(reasonable certainty)*	Extremely likely *(reasonable uncertainty)*
	Likelihood of infection	Very unlikely *(reasonable uncertainty)*	Very unlikely *(reasonable uncertainty)*	Very unlikely *(reasonable uncertainty)*
Combined exposure and infection likelihoods for each exposure group		Very unlikely	Very unlikely	Very unlikely
Combined likelihoods (farm infection, release, exposure and infection) for each		Very unlikely	Very unlikely	Very unlikely

Consequence assessment

The consequence assessment determined the potential magnitude of impacts on the abundance and diversity of Fraser River Sockeye Salmon, assuming that at least one susceptible wild fish has been infected with *A. salmonicida* released from infected Atlantic Salmon farms in the Discovery Islands area. The consequence to diversity was assessed based on the consequence to abundance.

Based on the likelihood assessment, it was determined that it is unlikely that Atlantic Salmon infected with *A. salmonicida* would be present on farms in the Discovery Islands area. In years without *A. salmonicida* infections on Atlantic Salmon farms, there would be no consequence to the number of returning adults and diversity of Fraser River Sockeye Salmon. However, during a year with *A. salmonicida* infections on Atlantic Salmon farms in the Discovery Islands area, fish health records indicate that at most one farm would have *A. salmonicida* infected Atlantic Salmon in any given month of the year.

Figure 3 illustrates the potential outcomes resulting from the infection of at least one susceptible Pacific salmon with *A. salmonicida* released from Atlantic Salmon farms located in the Discovery Islands area.

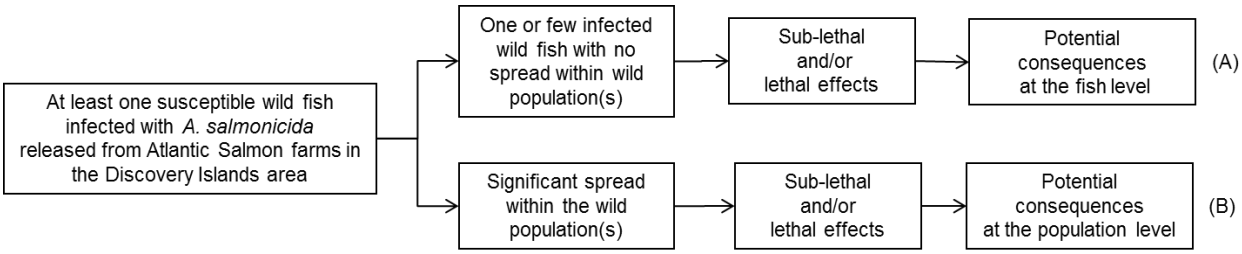

Figure 3. Potential outcomes resulting from at least one susceptible wild fish infected with Aeromonas salmonicida *released from Atlantic Salmon farms located in the Discovery Islands area.*

As the estimated waterborne concentration of *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area is lower than the lowest infectious concentration reported for *A. salmonicida* in salmonids, infection would most likely result from the direct contact of one or a few Pacific salmon with infected farmed Atlantic Salmon inside the net pens rather than through waterborne exposure of fish swimming through dispersed plumes.

Following exposure with diseased farmed Atlantic Salmon inside a net pen, whether or not the infected Pacific salmon would then transfer *A. salmonicida* to other susceptible fish, spreading the infection in the population depends on the probability of susceptible individuals to make contact with an infectious individual, the environmental conditions, and parameters specific to *A. salmonicida* survival and reproduction in the host. This also depends on the density of the population as well as other factors such as ecological interactions and fish behaviour.

Under experimental conditions, the density at which no detectible transmission of *A. salmonicida* was observed between Chinook Salmon fry in freshwater was 30 fish/m^3. This density is three orders of magnitude higher than the highest estimated average density of juvenile Fraser River Sockeye Salmon (0.03 fish/m^3) in the Discovery Islands area based on catch data from purse seining in the Strait of Georgia (Neville et al., 2013; Freshwater et al., 2017). Although based on surrogate information, this suggests that it is unlikely that the critical density of the host population required for the effective transmission of *A. salmonicida* and progression of the disease would be met for juvenile Fraser River Sockeye Salmon.

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

For adult Fraser River Sockeye Salmon, exposure to *A. salmonicida* within net pens is unlikely, the consequence from exposure of *A. salmonicida* released from a farm with infected Atlantic Salmon was considered.

The time between exposure to waterborne *A. salmonicida* and, if infected, mortality can be up to 24 days for Atlantic Salmon in saltwater (reported by Rose et al. (1989) in 75 to 115 g Atlantic Salmon in saltwater). Returning Fraser River Sockeye Salmon can take up to a month to reach spawning grounds (Stoddard, 1993). This suggests that some returning Sockeye Salmon, if infected, could reach spawning grounds with signs of furunculosis.

To explore the conditions under which *A. salmonicida* could spread within the adult population during migration to the spawning grounds, a stochastic, frequency-dependent compartmental susceptible-exposed-infected-recovered (SEIR) model with disease-induced mortality adapted from Keeling and Rohani (2007) was built. Results indicate that an infection acquired in the Discovery Islands area is not expected to significantly spread (i.e., <1% mortality, the threshold between a consequence of negligible and minor) within the returning adult Sockeye Salmon population prior to spawning. Refer to Mimeault et al. (2019) for more details on the parameters for the SEIR model.

As the potential consequences to Fraser River Sockeye Salmon from exposure to *A. salmonicida* released from Atlantic Salmon farms in the Discovery Islands area was concluded to be at the individual fish level, the consequences to diversity from exposure to *A. salmonicida* over two Sockeye Salmon generations (eight years) was considered, but determined to not represent a greater potential consequence than at the fish level.

Given the assessment that there would not be significant spread of infection within the returning adult Sockeye Salmon population prior to spawning, it was concluded with reasonable uncertainty that the potential magnitude of consequence to the population abundance or diversity of Fraser River Sockeye Salmon would be negligible.

As the direct magnitude of consequences on Fraser River Sockeye Salmon were determined to be negligible and there is no evidence to suggest that indirect consequences through changes in prey or predator populations would be of higher magnitude that direct ones, it was concluded with reasonable uncertainty that the potential magnitude of indirect consequences to both the abundance and diversity of Fraser River Sockeye Salmon resulting from an infection with *A. salmonicida* in other Pacific salmon species attributable to Atlantic Salmon farms in the Discovery Islands area would be negligible.

Risk estimation

The estimated risks to the abundance and diversity of Fraser River Sockeye Salmon are based on the results of the likelihood and consequence assessments. The risk categorization of minimal, moderate and high were determined and defined in collaboration with DFO's Ecosystem and Oceans Sciences and Fisheries Management sectors (Mimeault et al., 2017). They are aligned with relevant scales of consequences for fisheries management and policy

purposes, existing policy and current management risk tolerance relevant to the risk assessments.

Under the current fish health management practices, the risk to the abundance of Fraser River Sockeye Salmon as a result of an *A. salmonicida* infection attributable to Atlantic Salmon farms operating in the Discovery Islands area is minimal (Figure 4).

Likelihood							
	Extremely likely						
	Very likely						
	Likely						
	Unlikely						
	Very unlikely	X					
	Extremely unlikely						
		Negligible	Minor	Moderate	Major	Severe	Extreme
		Consequences to Fraser River Sockeye Salmon abundance					

Figure 4. Risk matrix for combining the results of the assessment of the likelihood of Aeromonas salmonicida *infection in wild fish attributable to Atlantic Salmon farms in the Discovery Islands area and magnitude of consequences to Fraser River Sockeye Salmon abundance. Green, yellow and red, respectively, represent minimal, moderate and high risk. The X indicates the risk estimate.*

Under the current fish health management practices, the risk to the diversity of Fraser River Sockeye Salmon as a result of an *A. salmonicida* infection attributable to Atlantic Salmon farms operating in the Discovery Islands area is minimal (Figure 5).

Likelihood							
	Extremely likely						
	Very likely						
	Likely						
	Unlikely						
	Very unlikely	X					
	Extremely unlikely						
		Negligible	Minor	Moderate	Major	Severe	Extreme
		Consequences to Fraser River Sockeye Salmon diversity					

Figure 5. Risk matrix for combining the results of the assessment of the likelihood of Aeromonas salmonicida *infection in wild fish attributable to Atlantic Salmon farms in the Discovery Islands area and magnitude of consequences to Fraser River Sockeye Salmon diversity. Green, yellow and red, respectively, represent minimal, moderate and high risk. The X indicates the risk estimate.*

Sources of Uncertainty

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

Uncertainties in the likelihood assessment

The main uncertainties related to the likelihood assessment are attributed to the lack of data to estimate prevalence of *A. salmonicida* in farmed Atlantic Salmon in marine net pens, reliance on a single laboratory study to estimate the shedding rates from *A. salmonicida*-infected Atlantic Salmon in saltwater, and that the minimal infectious and lethal doses of *A. salmonicida* in Sockeye Salmon in the saltwater are unknown.

There continues to be variability and knowledge gaps about precise migration routes of juvenile Fraser River Sockeye Salmon through the Discovery Islands area.

Uncertainties in the consequence assessment

The main uncertainties in the consequence assessments for both abundance and diversity resulted from the lack of information on disease spread within migrating fish populations, the lack of data on furunculosis mortality in wild Sockeye Salmon and other Pacific salmon species and the lack of knowledge of the consequences at the population level resulting from sub-lethal infections with *A. salmonicida*.

CONCLUSIONS

Characterization of *Aeromonas salmonicida* and furunculosis

Furunculosis is a septicemic bacterial disease found principally in salmonid fishes, caused by infection with *Aeromonas salmonicida*. The pathogen is transmitted horizontally. Information about interspecific and intraspecific variability in susceptibility within and across salmonid species is limited, however, all salmonid species are considered susceptible to *A. salmonicida* infection and disease.

Furunculosis has been reported on marine Atlantic Salmon farms in BC; however, there were no audit-based farm-level diagnoses attributable to furunculosis in the Discovery Islands area between 2002 and 2016. Health management and biosecurity practices undertaken by marine aquaculture companies, such as 100% vaccination, egg disinfection, and disinfection of farm equipment likely play a role in the limiting the occurrences of *A. salmonicida* and furunculosis. Despite these management practices, vaccinated fish may develop furunculosis after a stress event if they were exposed to *A. salmonicida* prior to vaccination.

The survival of *A. salmonicida* in the marine environment is influenced by factors such as temperature, salinity, visible and ultraviolet radiation and the presence of particulate organic matter. *A. salmonicida* has been documented in marine sediments.

The minimum infectious or lethal doses of *A. salmonicida* in Atlantic and Pacific salmon are unknown; however, bath challenge studies reporting the lowest lethal and infectious doses were used as a proxy for the purposes of the risk assessment.

Aeromonas salmonicida transfer risk assessment

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

Two main factors influenced the attribution of the minimal risk. First, it was determined that it is very unlikely that Fraser River Sockeye Salmon would become infected with *A. salmonicida*

released from an Atlantic Salmon farm in the Discovery Islands area. Second, even in the very unlikely event that they would become infected, the infection would not be expected to spread within wild populations, hence the magnitude of consequences to both Fraser River Sockeye Salmon abundance and diversity would be negligible.

The main sources of uncertainties associated to the determination of the risk to Fraser River Sockeye Salmon due to *A. salmonicida* attributable to Atlantic Salmon farms in the Discovery Islands area are related to the likelihood of infection of wild fish due to three aspects: a lack of information about shedding rates in carriers; lack of knowledge of the duration and extent of interaction of Fraser River Sockeye Salmon with Atlantic Salmon farms; and the minimum infectious and lethal dose of *A. salmonicida* in Sockeye Salmon was derived from an experiment with Sockeye Salmon fry in freshwater.

Additionally, the uncertainty associated with the consequence assessment is due to the lack of data or information related to furunculosis mortality in Sockeye Salmon and other susceptible Pacific salmon species, the spread of infection within migrating populations of fish, and the consequences at the population level resulting from sub-lethal infections.

Conclusions of this risk assessment should be reviewed as new research findings fill knowledge gaps.

OTHER CONSIDERATIONS

The long-term impacts of changing climatic conditions on the bacteria, farmed salmon and wild salmon will need to be better understood and investigated.

The Discovery Islands area is not the only area along the migration route of Fraser River Sockeye Salmon where Atlantic Salmon farms are located.

An analysis of the risks associated with infection with more than one pathogen was not undertaken, but will be examined in a future risk assessment.

The application of laboratory studies of pathogens to the assessment of risk is influenced by the experimental methods and design, particularly as it relates to the determination of shedding rates and minimum infectious and lethal doses.

This risk assessment is based on current industry size and practices. If there is a change in the size or practices of the Atlantic Salmon aquaculture industry in the Discovery Islands area, further analyses would be required.

LIST OF MEETING PARTICIPANTS

Name	Affiliation
Ackerman, Paige	Fisheries and Oceans Canada
Bianucci, Laura	Fisheries and Oceans Canada
Boily, France	Fisheries and Oceans Canada
Bruneau, Nathalie	Canadian Food Inspection Agency (CFIA)
Bruno, David	Marine Scotland Science
Burgetz, Ingrid	Fisheries and Oceans Canada
Byrne, Philip	Fisheries and Oceans Canada
Fuller, Chad	First Nations Fisheries Committee of BC

Name	Affiliation
Gardner, Ian	Atlantic Veterinary College UPEI
Garver, Kyle	Fisheries and Oceans Canada
Hewison, Tim	Grieg Seafood
Higgins, Mark	Fisheries and Oceans Canada
Holt, Carrie	Fisheries and Oceans Canada
Jakob, Eva	Aqua Nutrition Cargill
Johnson, Stewart	Fisheries and Oceans Canada
Jones, Simon	Fisheries and Oceans Canada
Malcolm, Gabrielle	Fisheries and Oceans Canada
Milligan, Barry	Cermaq Canada
Mimeault, Caroline	Fisheries and Oceans Canada
Olivier, Gilles	Fisheries and Oceans Canada
Parsons, Jay	Fisheries and Oceans Canada
Paylor, Adrienne	Fisheries and Oceans Canada
Peterman, Randall	Simon Fraser University
Powell, Mark	Institute of Marine Research
Proboszcz, Stan	Watershed Watch
Rhodes, Linda	National Oceanographic Atmospheric Administration
Roth, Myron	BC Ministry of Agriculture
Saksida, Sonja	Canadian Food Inspection Agency (CFIA)
Siah, Ahmed	BC Centre for Aquatic Health Sciences
Struthers, Alistair	Fisheries and Oceans Canada
Trudel, Marc	Fisheries and Oceans Canada
Wade, Joy	Fundy Aqua Services
Wan, Di	Fisheries and Oceans Canada
Werring, John	David Suzuki Foundation

(comments only):

Name	Affiliation
Dalsgaard, Inger	Technical University of Denmark
Davies, Robert	University of Glasgow
Purcell, Maureen	U.S. Geological Survey
Stevenson, Roselynn	University of Guelph
St-Hilaire, Sophie	Atlantic Veterinary College UPEI

SOURCES OF INFORMATION

This Science Advisory Report is from the November 6–8, 2018 national advisory meeting on Assessment of the risk to Fraser River sockeye salmon due to bacteria causing systemic infections transferred from Atlantic salmon farms located in the Discovery Islands area, British

Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Austin, B. and Austin, D. A. 2016. Aeromonadaceae representative (*Aeromonas salmonicida*). *In* Bacterial fish pathogens. Springer. pp 215-321.

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

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.

DFO. 2010. Pathways of effects for finfish and shellfish aquaculture. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/071.

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

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

GESAMP. 2008. Assessment and communication of environmental risks in coastal aquaculture. *In* Reports and Studies GESAMP. Rome, Italy. FAO 76: 198 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, BC. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/074. v + 30 p.

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

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

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

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

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

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

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

McCarthy, D. H. and Roberts, R. J. 1980. Furunculosis of fish: the present state of our knowledge. *In* Advances in aquatic microbiology. Academic Press. Vol 2: pp 293-341.

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. 2019. Assessment of the risk to Fraser River Sockeye Salmon due to *Aeromonas salmonicida* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/017. In press.

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

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

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

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

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

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

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

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

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

THIS REPORT IS AVAILABLE FROM THE:

Canadian Science Advisory Secretariat (CSAS)
National Capital Region
Fisheries and Oceans Canada
200 Kent Street
Ottawa, ON K1A 0E6

Telephone: 613-990-0293
E-Mail: csas-sccs@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

ISSN 1919-5087

Correct Citation for this Publication:

DFO. 2020. Advice from the 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. Sci. Advis. Rep. 2019/017.

Aussi disponible en français :

MPO. 2020. Avis découlant de l'évaluation du risque pour le saumon rouge du fleuve Fraser attribuable au transfert de la bactérie Aeromonas salmonicida *à partir des fermes d'élevage de saumon atlantique situées dans la région des Îles Discovery (Colombie-Britannique). Secr. can. de consult. sci. du MPO, Avis sci. 2019/017.*