Fisheries and Oceans Canada | Pêches et Océans Canada

Ecosystems and Oceans Science | Sciences des écosystèmes et des océans

ADVICE FROM THE 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 AREA, BRITISH COLUMBIA

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

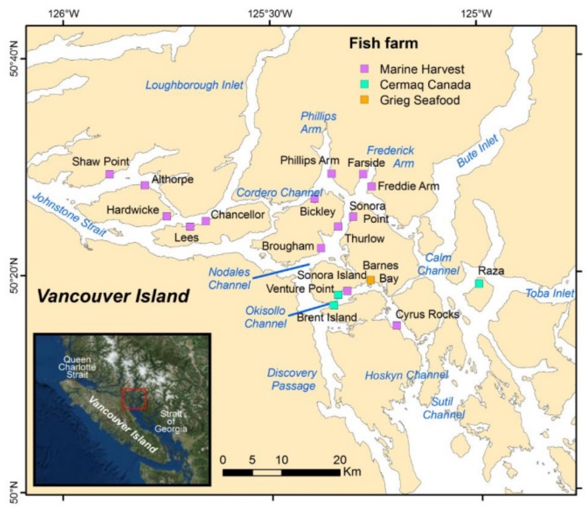

Figure 1. Atlantic Salmon farms in the Discovery Islands, British Columbia.

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 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 will be provided through a series of pathogen transfer risk assessments, the first one focusing on Infectious Hematopoietic Necrosis Virus (IHNV). This well characterised pathogen is known to have caused disease on Atlantic Salmon farms in the Discovery Islands (St-Hilaire et al., 2002; Saksida, 2006). The risks associated with other pathogens also known to cause disease on marine

Atlantic Salmon farms in the Discovery Islands will be assessed in subsequent processes.

This Science Advisory Report is from the December 5-8, 2016 national advisory meeting on Assessment of the risk to Fraser River Sockeye Salmon due to Infectious Hematopoietic Necrosis Virus transfer from Atlantic Salmon farms located in the Discovery Islands, British Columbia. Additional publications from this meeting will be posted on the DFO Science Advisory Schedule as they become available.

SUMMARY

IHNV Transfer Risk Assessment

- The assessment concluded that the risk posed to Fraser River Sockeye Salmon abundance and diversity by IHNV infection attributable to Atlantic Salmon farms in the Discovery Islands is **minimal** under the current fish health management practices.
- Two main factors contributed to the resulting minimal risk:
  - the likelihood of an IHN disease outbreak on Atlantic Salmon farms in the Discovery Islands is estimated to be **very unlikely** with **reasonable certainty** given current health management practices including vaccination against IHN disease; and
  - the likelihood for juvenile Fraser River Sockeye Salmon to be infected and become diseased due to IHNV released from Atlantic Salmon farms is estimated to be **extremely unlikely** with **reasonable uncertainty** given current health management practices (i.e., vaccination, surveillance for early detection and depopulation) that limit the amount of potential IHNV shed into the environment from infected farms.
- The overall likelihood assessment, including separate disease, release, exposure, and infection assessments, was supported by the following key information:
  - regulatory requirements and farm level practices (i.e., vaccination, rapid detection, and depopulation upon confirmation of IHNV);
  - juveniles and adult Sockeye Salmon migrate through the Discovery Islands;
  - once Atlantic Salmon develop IHN disease, virus is shed into the environment;
  - oceanographic processes will transport water away from farms;
  - juvenile Sockeye Salmon are the most IHNV susceptible Sockeye Salmon life stage; and
  - all estimated maximum IHNV waterborne concentrations in net pens and plumes were below the laboratory based estimates of IHNV minimum lethal dose for juvenile Sockeye Salmon.
- Uncertainty in this assessment is driven by the lack of knowledge of:
  - the precise residence time of both juvenile and adult Sockeye Salmon in the Discovery Islands, local migration routes and occurrence around Atlantic Salmon farms (i.e., what proportion of migrating Sockeye Salmon are exposed to farms, how close, and for how long);
  - IHNV mortality rates for post-smolt Sockeye Salmon; and
  - other potential impacts of an exposure of Sockeye Salmon to IHNV at marine life stages (e.g., sub-lethal and cumulative effects).

- For the purpose of the assessment, a number of key assumptions were made including, for example:
  - current management practices are followed and will be maintained, including IHN vaccination of all farmed Atlantic Salmon, surveillance for early detection, and eradication of infected fish within 14 days of confirmation of positive samples;
  - the APEX-IHN® vaccine has a 95% efficacy in farmed Atlantic Salmon;
  - exposure to a minimum concentration of 10^8 pfu/m^3 (plaque forming units per cubic metre) for an hour or more is required to cause infection and disease in juvenile Sockeye Salmon;
  - juvenile Sockeye Salmon had not developed immunity to IHNV (i.e., are naïve) upon exposure to IHNV released from Atlantic Salmon farms; and
  - all IHNV infections in susceptible Sockeye Salmon results in disease and direct mortality.
- The risk assessment framework and conceptual model used to assess risk of pathogen transfer was accepted and suggestions were made for improvements to future risk assessments.

The risk assessment was informed by four background documents of which the most relevant elements are summarized below.

Oceanographic and Environmental Conditions of the Discovery Islands

- The physical oceanography of the Discovery Islands is characterized by strong tidal currents, significant freshwater flow due to river runoff and snowmelt, and surface currents driven by winds that vary in speed and direction due to the steep topography typical of fjord regions.
- Oceanographic conditions in the Discovery Islands region vary both seasonally and regionally, with a monthly average temperature range of 6 to 14ºC (measured minimum and maximum of 3 and 24ºC), monthly average salinity range between 23 and 31 (measured minimum and maximum of close to 0 and 32) and monthly average levels of dissolved oxygen ranging between 170 and 340 mmol/m^3 (measured minimum and maximum of 50 and 550 mmol/m^3). Waters in the central Discovery Islands (in the vicinity of the fish farms) are generally well-mixed due to the strong tidal currents.
- UV varies seasonally and is reduced during periods of cloudiness. As UV penetrates the water it is reduced exponentially to less than one percent of its surface value within 10 m.
- Tidal currents of at least 1 m/s are common and can transport water over 14 km in one direction until the tide changes.
- River discharges throughout the region force surface currents that generally flow seaward.
- Wind can drive surface currents on seasonal and shorter time scales.
- A Discovery-region hydrodynamic model has been developed to simulate the circulation due to the forcing fields described above.
- A coupled particle tracking model has also been developed to simulate the dispersal of particles. The dispersion time and spatial scales vary depending on the tides, river discharges and winds.

British Columbia Farmed Atlantic Salmon Health Management Practices

- In BC there are a suite of regulatory requirements for fish health management on farms that influence the occurrence and transmission of pathogens. Additional fish health practices that the farms implement are part of best practices, and in some cases to obtain and maintain third party certification.
- There are best management practices and standard operating procedures to prevent, manage, and monitor pathogens and disease (e.g., voluntary vaccination, presence of trained fish health personnel on farms, cleaning and disinfecting protocols, and movement controls of people and equipment, collection and analysis of syndromic information, etc.).
- There are practices that are designed to contain the spread of a pathogen from the farm once a disease has been detected on the farm (e.g., treatment and management options, early eradication, viral management plan with enhanced movement controls, and communication among companies and with regulatory bodies, etc.).
- All companies currently voluntarily vaccinate smolts against IHNV.
- The British Columbia Pacific Aquaculture Regulations are outcome-based, and outlined in the Fish Health Management plans. Companies must document that they meet the required fish health concepts as part of the licence conditions and this is audited by DFO.
- Increases in mortalities must be reported to DFO as a condition of licence. Suspicions or detection of reportable diseases or infections must be reported to DFO and Canadian Food Inspection Agency (CFIA).

Characterization of Infectious Hematopoietic Necrosis Virus (IHNV)

- In British Columbia, IHNV is endemic and can occasionally cause disease in juvenile Sockeye Salmon, and rarely in Rainbow Trout/ steelhead trout, Chum Salmon and Chinook Salmon.
- With increasing size and later life-stage, Sockeye Salmon become less susceptible to IHN disease but are susceptible to infection. Adult Sockeye Salmon are refractory to IHN but can be infected.
- Atlantic Salmon smolts are highly susceptible to IHN with a minimal infectious lethal dose that is 10-100 times lower than for Sockeye Salmon smolts.
- IHN outbreaks have only occurred in non-vaccinated farmed Atlantic Salmon in British Columbia. Atlantic Salmon with IHN disease shed high quantities of virus at the terminal stages of disease.
- Vaccination of Atlantic Salmon against IHN using the highly efficacious APEX-IHN® vaccine reduces IHN disease and viral shedding and transmission.
- Over time, the concentration of IHNV in seawater is reduced through physical (e.g., sunlight - UV) and biological processes (e.g., microbial community), based on laboratory experiments.

Characteristics of Fraser River Sockeye Salmon Stocks, Biology and Ecology

- With the exception of the Harrison River type population, the majority of juvenile Fraser River Sockeye Salmon migrate northward through the Discovery Islands, usually from mid-May to mid-July with peak migration occurring in June.

- The residence time of individual juvenile Fraser River Sockeye Salmon in the Discovery Islands is estimated to range between 5 and 14 days and they have been observed in the vicinity of Atlantic Salmon farms; however, the proportion of the total population that migrates directly past the farms is unknown.
- The proportion of adult Fraser River Sockeye Salmon migrating through the northern entrance to the Strait of Georgia (“diversion rate”) varies among years (average: 52%; range 10% to 96%) and increases within a migration period.
- Adult Fraser River Sockeye Salmon take approximately three days to migrate southward through the Discovery Islands from late-June to early-October and have been observed in the vicinity of salmon farms; however, the proportion of the total return that migrates directly past the farms is unknown.
- Under the Wild Salmon Policy, there are 24 Fraser River Sockeye Salmon Conservation Units (CUs), 11 of which are of conservation concern.
- Fraser River Sockeye Salmon abundance is variable and in recent years has ranged annually from approximately 1.5 million to 28.2 million returning adults.
- Some CU’s exhibit cyclic four-year patterns in their return abundances (one large dominant year and three smaller abundance years) and some do not (similar abundances among years).

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 are science-based and do not include socio-economic considerations.

This advisory report is the consensus advice developed during the December 5-8, 2016 (Canadian Science Advisory Secretariat) CSAS scientific peer-review meeting that included international and national scientific experts. Information and current scientific knowledge necessary to inform the advice were reviewed in CSAS research documents related to:

- The oceanographic characteristics of the Discovery Islands, including predictions on the movement of particles away from existing farm sites in the area.
- The fish health management practices on Atlantic Salmon farms that influence the transmission of pathogens between farmed Atlantic Salmon and wild fish populations in a marine environment.
- The characteristics of IHNV infection and disease, host susceptibility, and its prevalence and infection dynamics in British Columbia.
- The characteristics of Fraser River Sockeye Salmon stocks, and the relevant biological and ecological factors related to the assessment of risk.

The above supporting CSAS research documents were reviewed and used to reach the remaining objectives of the meeting:

- Review the qualitative risk assessment on Fraser River Sockeye Salmon abundance and diversity due to IHNV transfer from Atlantic Salmon farms located in the Discovery Islands.
- Review the uncertainties associated with the estimation of the risk to Fraser River Sockeye Salmon abundance and diversity.
- If risk assessment outcomes warrant, provide advice on additional measures that would reduce the risk to Fraser River Sockeye Salmon abundance and diversity due to IHNV transfer from Atlantic Salmon farms in the Discovery Islands.

ANALYSIS

Oceanographic and Environmental Conditions of the Discovery Islands

Chandler et al. (2017) provide a review of the oceanography and environmental conditions relevant to pathogen transfer risk assessments in the Discovery Islands. The key findings, and their related uncertainties, to inform pathogen transfer environmental risk assessments in the area are summarized below.

The Discovery Islands area is a complex network of islands, narrow channels and deep fjords (Figure 1 and Figure 2) characterized by significant seasonal and spatial variations in oceanographic conditions. Current knowledge about the ocean circulation in the Discovery Islands is mainly derived from Acoustic Doppler Current Profiler moorings deployed from 2009 to 2015 and model simulations dating from April to October 2010.

The maximum near surface (0 to 30 m) temperature values are usually observed from June to August. The maximum spring and summer near surface water temperatures in eastern channels are warmer (>20ºC) than those of the western channels (<15ºC); however, the coldest observed water temperatures are similar throughout the Discovery Islands. Seasonal historical climatology data show a 2.5ºC variation in temperature with cooler values at the heads of fjords (Figure 3). Refer to Chandler et al. (2017) for more details.

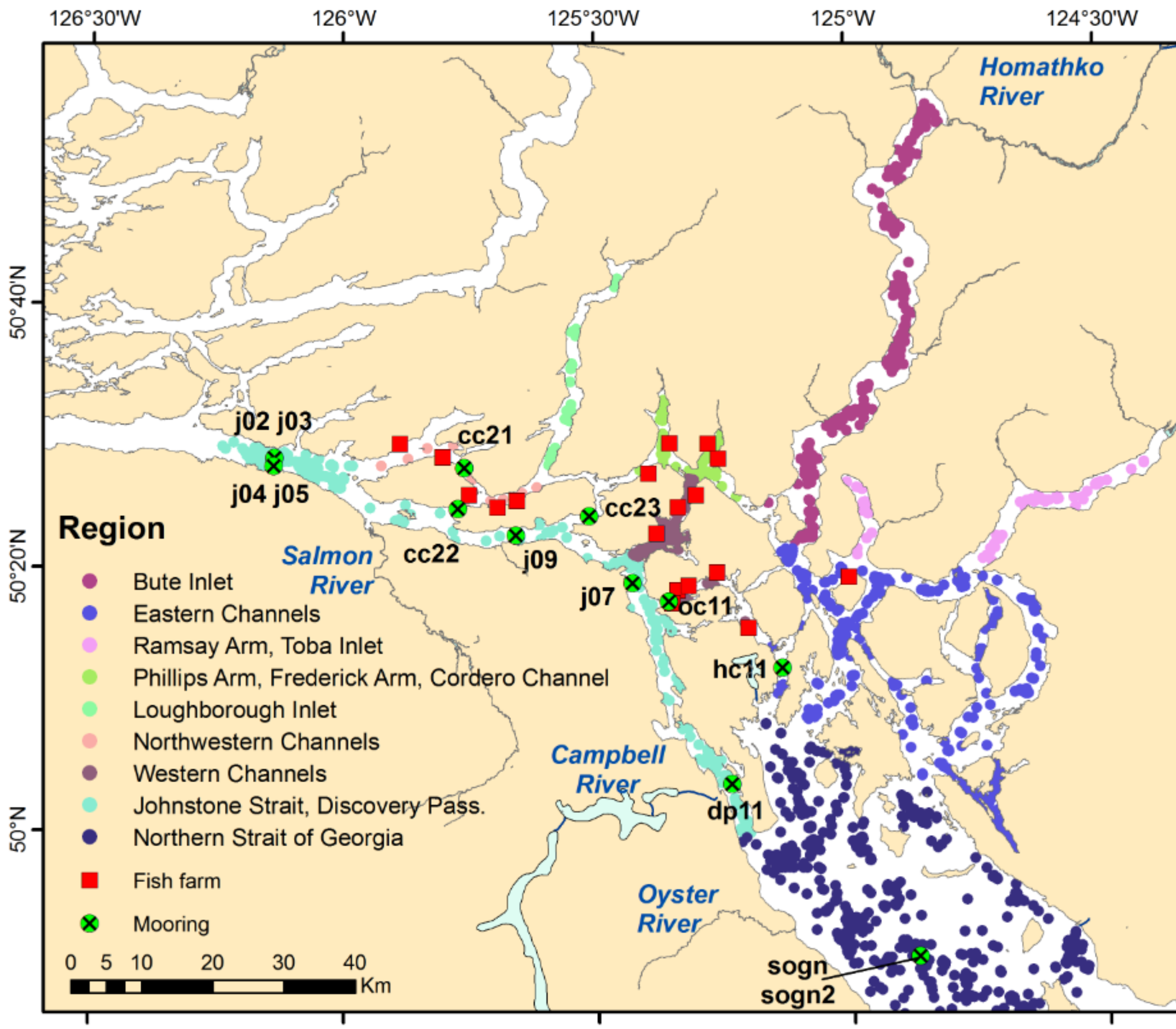

Figure 2. Map of the Discovery Islands showing regions based on geographical and water properties (salinity, temperature and oxygen). Data derived from DFO oceanographic archives (1932 – 2015). Dots represent location of oceanographic profiles and crosses within circles represent location of moored temperature and salinity records. Alphanumeric codes correspond to mooring codes (see Chandler et al. (2017) for more details).

Surface salinity varies spatially across the Discovery Islands being lower in the fjords and higher in regions with strong tidal mixing (e.g., southern Discovery Passage) (Figure 3). Salinity also varies with depth, with lower salinity close to the surface and higher salinity at deeper depths. The vertical salinity profiles also differ among regions. Freshwater discharge from rivers affects the salinity levels, for example water from the Campbell River influences salinity levels in the top two to three meters near the mouth of the river but the stratification disappears with increased distance from the river mouth.

Bute Inlet is usually fresher than other inlets due to consistent river runoff throughout the summer that results in <15 salinity water from May to October. The Ramsay Arm and Toba Inlet regions have the second most significant freshwater events with minimal salinity values, generally occurring in July. The eastern channels can be relatively fresh (salinity <20), which likely results from the mixing of waters from Bute Inlet, Ramsay Arm and Toba Inlet. The western channels region, to which Loughbourough Inlet is connected, is not fresher than 27 salinity units. Johnstone Strait and Discovery Passage have lower salinity peaks slightly earlier (early to late June) than the Northern Strait of Georgia (end of June).

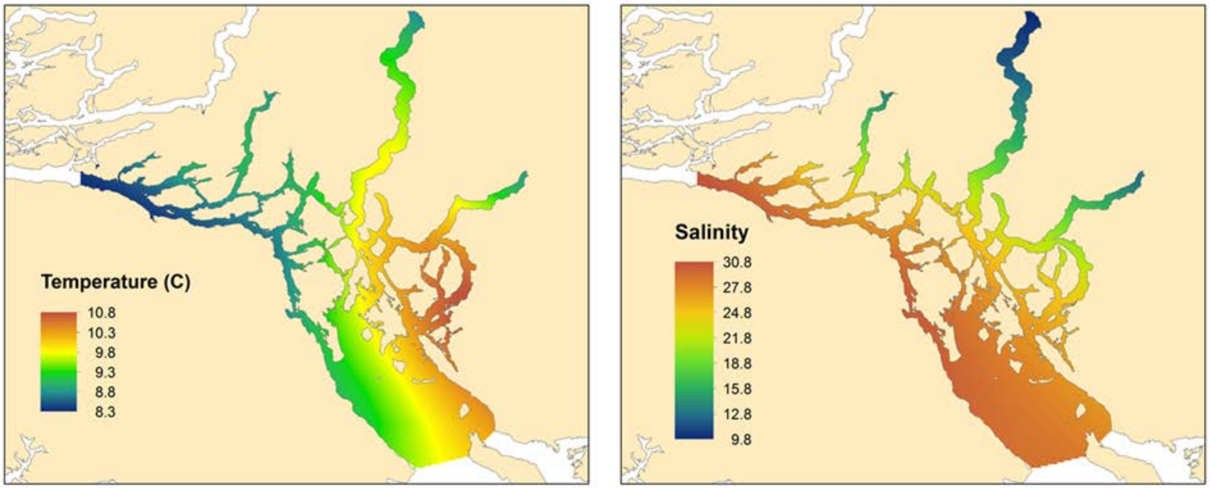

Figure 3. Surface temperature and salinity fields used to initialize FVCOM based on CTD data collected over several years in the spring in the Discovery Islands. Adapted from Foreman et al. (2012).

The range of dissolved oxygen concentrations in the Discovery Islands has been observed to be between 50 and 550 mmol/m^3, with monthly average values ranging from 170 to 340 mmol/m^3. Higher dissolved oxygen concentrations are nearer the surface as evident in observations made in the Northern Strait of Georgia and Eastern Channel. Dissolved oxygen values at depth (30 to 60 m) are similar throughout the region.

There is an exponential decay of UV radiation as it penetrates down the water column from the surface. Field measurements of UV in Nodales Channel and Toba Inlet in early September 2010 are presented in Figure 4.

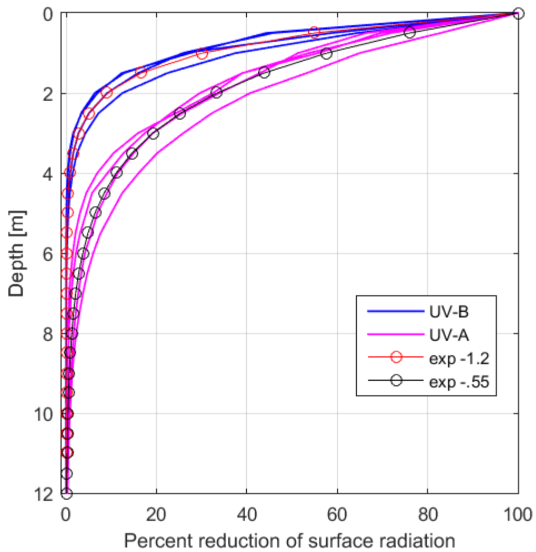

Figure 4. The attenuation of solar radiation with depth measured in Nodales Channel and at the entrance of Toba Inlet in the Discovery Islands in September 2010. UV-A and UV-B measurements and fits of exponential decay with respective coefficients of -0.55 and -1.2 are shown.

Solar radiation varies with season, topography (shading) and cloud cover. Figure 5 illustrates the solar radiation data from Cinque, a site that is exposed to sunlight from all directions during the day.

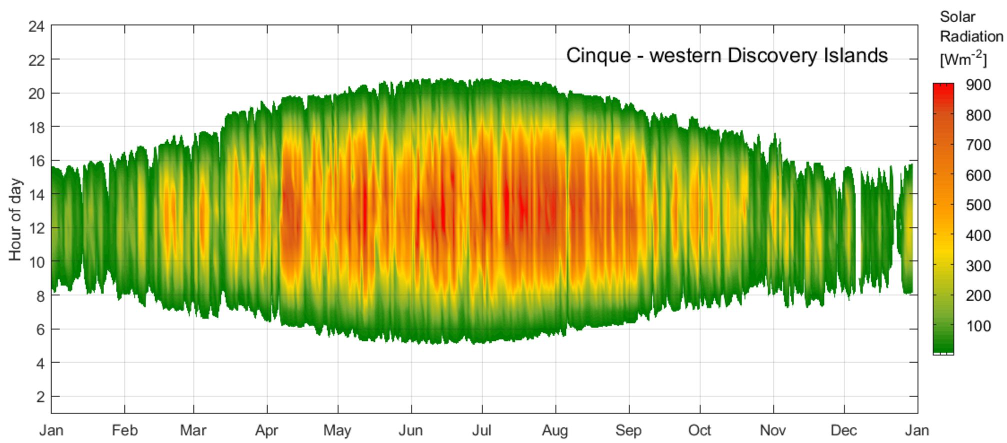

Figure 5. Solar radiation measured in 2010 and 2011 at a DFO weather station on Cinque Island in the Discovery Islands, showing seasonal and daily variations, and events of high solar radiation.

In the Discovery Islands, water currents are generally a combination of three components: tidal streams (that vary hourly to daily), buoyancy currents (primarily due to freshwater inputs, which are often referred to as estuarine flows) and wind-driven currents (near surface forcing and subsequent mixing during strong winds) (Chandler et al., 2017). Some of the strongest tidal currents in the world, up to 7.8 m/s in Discovery Passage (reported in Lin et al. (2011)), are found in the Discovery Islands. Tidal currents can move particles back and forth in a given area due to the six hour reversal of direction from flood and ebb flows. The length scale of these excursions depends on the current velocity, for example a 12.4 hour tidal current of 1 m/s can transport water over 14 km in one direction until the tide changes. However, when tidal current gradients are strong, as is the case for many areas in the Discovery Islands, tidal currents can also contribute to the net transport of particles over several tens of kilometers.

In Discovery Passage, estuarine flows generally force the surface layer northward and a returning flow at depth (Thomson, 1981). Estuarine flows are particularly important in influencing circulation throughout the water column during the spring freshet, when runoff from snow melt will introduce a significant volume of fresh water, particularly in inlets where there are high river discharges, such as Bute Inlet and Toba Inlet.

Freshwater discharge varies considerably between rivers and seasons with annual average water discharges for the Homathko, Salmon and Oyster rivers of, respectively, 259 ± 226 m^3/s, 61 ± 26 m^3/s, and 13 ± 6 m^3/s (Chandler et al., 2017). In the Discovery Islands, water discharge from rivers located on the BC mainland side generally peaks mid-summer being primarily driven by snow and glacial melt, while water discharge from rivers located on Vancouver Island are primarily driven by rainfall and peak in the autumn and winter (Foreman et al., 2015a).

During periods when tidal forcing or buoyancy forcing is reduced, the wind plays an important role in determining the speed at which the surface current flows. The direction is generally determined by the orientation of the channel. Analysis of 2010-2011 hourly wind observations reveals that the strongest winds, those most likely to influence the surface flows, are along Johnstone Strait and Discovery Passage and in the open waters of the northern Strait of Georgia (Chandler et al., 2017). The dominant winds are from the northwest and southeast, in both strength and frequency of occurrence.

Hydrodynamic models are used to simulate the ocean circulation based on observed data and solutions of mathematical equations that approximate the governing physics. Foreman et al. (2012, 2015a) incorporated available observational data on temperature, salinity, tides, winds and freshwater input to force and evaluate a Finite-Volume Community Ocean Model (FVCOM) simulation of the water circulation in the Discovery Islands for April to October 2010. The model results suggested that the April mean flows were the result of a combination of the freshwater input from the rivers and tides with little contribution from the wind at this time of the year. Variations in speed, direction, and the presence of eddies were also observed. Generally good agreement was found between the model and observed current components for the months of April and July. Comparisons of model and observed (farm) salinities and temperatures can also be found in Chandler et al. (2017).

The April to October 2010 simulation shows significant seasonal variability in the near-surface, non-tidal currents. Though some changes can be attributed to seasonality in the winds, as described above, most are due to changes in the freshwater discharges and resultant near-surface estuarine flows. Consistent with measured river discharges, the FVCOM model runs show generally larger surface estuarine flows in July than any of the other six months. The tides are significant contributors to these fields, particularly in regions like southern Discovery Passage and Arran Rapids where maximum speeds can exceed 7 m/s. However, except in regions with strong tidal current gradients, tidal currents generally move particles back and forth with little net transport; the primary current components that move pathogens and other particulate matter significant distances are the estuarine flows and the wind-driven currents.

Using the outputs of the ocean current model, Foreman et al. (2015b) simulated the dispersal of particles in the Discovery Islands for April to October 2010 using particle tracking models. These simulations are referred to as passive particle tracking when the particles are assumed to have no biological, chemical or behavioural characteristics that could affect the decay, dispersal or virulence of the particle. The results of the passive particle tracking models simulate the dispersal due only to the oceanographic processes included in the model.

Figure 6 illustrates the dispersion clouds resulting from a simulation conducted under April to October 2010 conditions in which passive particles were released at the surface from 32 farms located in the Discovery Islands and tracked for ten days. Based on the predominant northwestward surface estuarine flow in the area, the simulation indicated that particles could reach Johnstone Strait within 2.5 days (Foreman et al., 2015b). The simulation also indicated that a small percentage of particles travelled southeastward and reached the Strait of Georgia within five days. Based on additional passive particle simulations, dispersion is also expected to vary seasonally; particles could travel 10% further and disperse 31% more widely in July compared to April 2010 when released from the same points (Foreman et al., 2015a).

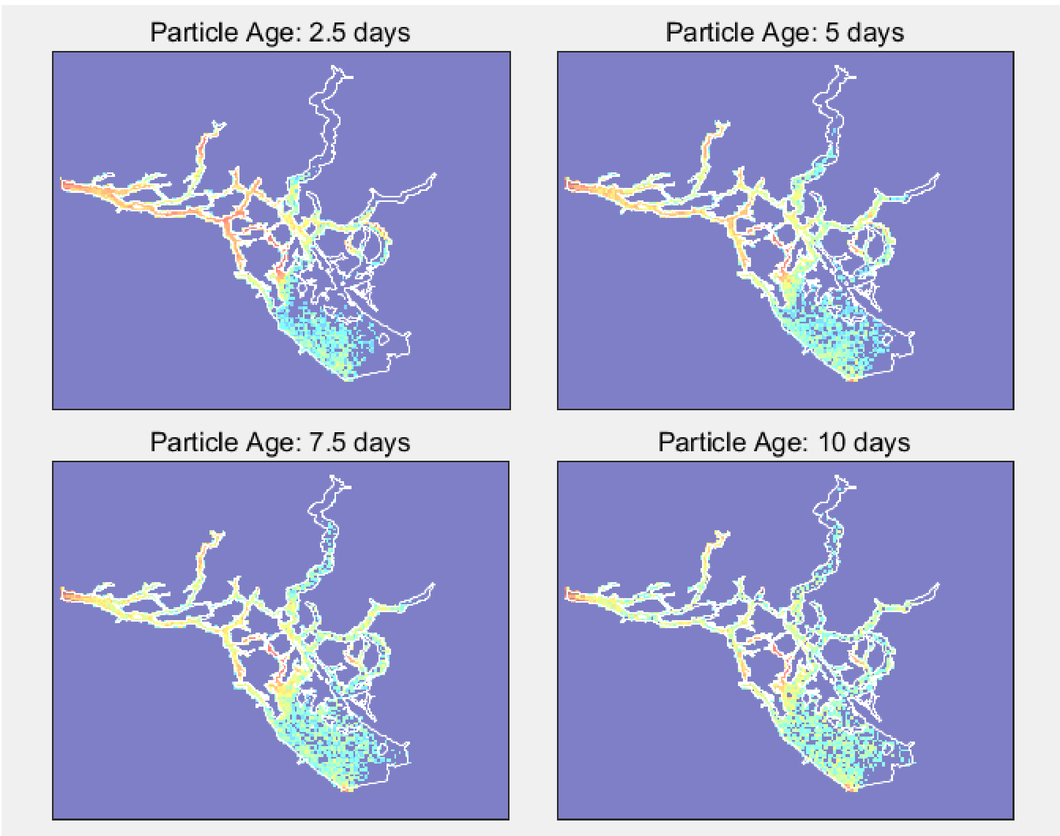

Figure 6. Dispersion clouds arising after 2.5, 5, 7.5, and 10 days from hourly passive particle releases over the month of April, 2010 at 32 farms within the Discovery Islands area (including farms considered in the risk assessment). Red and turquoise colours, respectively, denote higher and lower concentrations. Adapted from Foreman et al. (2015b).

The scope and accuracy of the above simulation is an important consideration for environmental risk assessments. When the simulated dispersal trajectories were compared to actual trajectories of GPS tracked drifters released in Knight Inlet, north of the Discovery Islands, the simulated and observed trajectories were similar in direction. However, after six hours, the drifters had not travelled as far as the majority of modelled particles (Foreman et al., 2015b). This initial inconsistency was not observed 24 hours after release suggesting that the passive particle tracking model provided realistic simulations of expected trajectories and traveled distances at time scales greater than six hours.

British Columbia Farmed Atlantic Salmon Health Management Practices

Wade (2017) provides a review of the fish health management licencing requirements and voluntary practices (including the Viral Management Plan) on Atlantic Salmon farms in British Columbia relevant to pathogen transfer risk assessments. The elements most relevant to inform the IHNV transfer risk assessment are summarized here.

DFO is responsible for issuing aquaculture licences for marine finfish, shellfish and freshwater operations in British Columbia. Licences are issued under the authority of the *Fisheries Act* and are subject to the provisions of the *Fisheries Act* and regulations, including the Pacific Aquaculture Regulations and the Aquaculture Activities Regulations. In addition, the Canadian Food Inspection Agency (CFIA) has responsibility under the *Health of Animals Act* for issuing import and movement control permits, as well as for disease response, particularly for federally reportable, immediately notifiable and annually notifiable diseases that are identified in the Reportable Disease Regulations. In addition to actions associated with diseases identified in the Regulations, action can be taken at any time, if necessary, for other diseases.

Under the Pacific Aquaculture Regulations, as a condition of licence, each company must have a Salmonid Health Management Plan and accompanying proprietary Standard Operating Procedures (SOPs). These SOPs along with other conditions of licence provide evidence of the biosecurity measures in place to mitigate disease events and minimize the spread of pathogens within and away from a farm should they occur. Other licence conditions which aid in the maintenance of healthy fish are production plans, requirements for fish transfer and fish health record keeping.

Biosecurity measures required as part of the Salmonid Health Management Plan include procedures that limit the introduction of pathogens onto a farm site through measures such as control of visitors, on-site disinfection requirements, transport protocols, etc. Additionally, there are Standard Operating Procedures to limit the transmission of a pathogen, including protocols related to the transport and handling of mortalities, cleaning and disinfection, and isolation and control of transport routes to limit the risks of cross contamination. Increases in mortalities must be reported to DFO as a condition of licence, and reporting of suspicions or detection of reportable diseases or infections to DFO and CFIA is mandatory.

Elements of these SOPs and other licence conditions are regularly audited by DFO. Farms are notified of any deficiencies and corrective measures must be taken. From 2011 to 2015, there were 465 audits of Atlantic Salmon farms in British Columbia. Many audits resulted in no deficiencies, the highest number of deficiencies was 83 in 2012 and the lowest was 52 in 2013. The average number of deficiencies per audit over five years was 0.77 ± 0.34, ranging from 0.51 in 2012 to 1.43 in 2011. As part of the audit program, tissue samples are taken for routine pathogen screening at accredited laboratories, and these results are compared to the reporting results submitted by each company as a condition of licence.

In addition to the regulatory requirements, the Atlantic Salmon farming companies have best management practices that they require to be implemented on-farm. These may be a combination of internal practices, BC finfish industry-negotiated practices (i.e., Viral Management Plan), and those required under third-party certification programs.

Key additional fish health management practices that all three companies have in place include the collection and analysis of syndromic information, such as environmental data, feeding information, abnormal behaviour, as well as pathogen screening of mortalities. While some of this information is required under licence conditions, the detail required for site management often exceed these requirements. For instance, in addition to the samples taken during an audit for disease screening, the companies also sample fresh mortalities on a routine basis for their own disease screening. Typically, from marine cage sites alone, Marine Harvest Canada samples over 4,800 fish per year for histology and approximately 900 for virology; Grieg Seafood tests over 1,000 fish per year for virology; and Cermaq Canada tests over 3,000 fish per year for various pathogens of concern. These estimates do not include broodstock or pre-transfer smolt testing.

Vaccination of Atlantic Salmon is not a requirement of licence; however, all companies voluntarily vaccinate their fish for pathogens including IHNV. The agreement to vaccinate fish and have a coordinated effort in mitigation of disease and response in an outbreak situation is formalized in the industry's Viral Management Plan, which was initially ratified in 2011. The Viral Management Plan is a Memorandum of Understanding among the three companies in conjunction with the BC Salmon Farmers' Association. As of 2015, the Viral Management Plan stipulates that the IHNV vaccine be used by all companies on all smolt before sea water entry. Vaccination is also a requirement of both the Best Aquaculture Practices Certification (BAP) and the Aquaculture Stewardship Council (ASC), in addition to other biosecurity oversight and fish health monitoring requirements. All farms in the Discovery Islands are certified through BAP and some farms are also in the process of being certified through the ASC. Refer to Wade (2017) for more details on the Viral Management Plan.

In addition to vaccination and enhanced biosecurity requirements during regular operations, the Viral Management Plan includes standard procedures that are followed in the case of an outbreak of a viral disease, providing a framework for structured and controlled actions in an outbreak situation. This is enacted whenever a finding of concern occurs, which, includes cases of unexpected increases in mortality in one or more cages on a site, or a substantial increase in the number of moribund fish causing specific concern. It may also include the presentation of clinical signs consistent with viral infection of concern in moribund or fresh mortalities or, when receiving preliminary positive results of a virus of concern from the laboratory. For reportable diseases, the CFIA and DFO National Aquatic Animal Health Program assumes oversight for sampling, testing and diagnostic confirmation. Sites are isolated and other companies are notified. The Viral Management Plan also includes specifics regarding index case management, ongoing management for areas with multiple positive findings, rapid depopulation and secure disposal of fish after receiving CFIA approval, and minimum fallow periods prior to repopulation (three months or one month after release from quarantine, whichever is longer).

Characterization of Infectious Hematopoietic Necrosis Virus (IHNV)

Garver and Wade (2017) provide a review of the characteristics of IHNV relevant to the IHNV transfer risk assessment. The most relevant elements are summarized here.

Infectious Hematopoietic Necrosis Virus (IHNV) is a virus that can result in an acute systemic disease called infectious hematopoietic necrosis (IHN) which has led to significant mortality in both wild and cultured salmon and trout populations (Bootland and Leong, 1999). Due to the contagious nature and potential to cause large losses of fish, IHN is listed as reportable to the World Organization for Animal Health (OIE) (Dixon et al., 2016).

Virus characterization

The primary mode of IHNV transmission is horizontal within and among wild salmon populations. Laboratory studies exposing fish to IHNV via immersion in virus contaminated water or through cohabitation with IHNV infected fish, have demonstrated that IHNV is transmitted and spread through waterborne exposure (Garver et al., 2013). However, transmission of the virus can also occur vertically when virus particles on the surface of the eggs infect the developing embryo (Garver and Wade, 2017).

The environmental stability of IHNV is affected by salinity, temperature, organic load, and microbial content of the water, as well as exposure to ultraviolet light. High concentrations of IHNV are inactivated within days in naturally occurring river and ocean waters or within minutes if subjected to sunlight (Garver et al., 2013). Consequently higher concentrations of waterborne IHNV may accumulate during the winter months when water temperatures and sunlight are significantly less than that observed during spring and summer months.

Disease/host interaction

Evidence from natural infections and controlled laboratory exposure studies indicate that IHNV has a broad host range. While primarily identified in salmonids, IHNV has also been found in non-salmonids and invertebrates. Infection can cause disease in some hosts and may be transient in others.

In British Columbia, IHNV is most commonly detected within Sockeye Salmon (*Oncorhynchus nerka*) populations, and less commonly, in Rainbow Trout /steelhead trout (*O. mykiss*), Chum Salmon (*O. keta*) and Chinook Salmon (*O. tshawytscha*). Long-term monitoring of British Columbia Sockeye Salmon stocks from the Skeena, Fraser, and Columbia River watersheds has revealed that the annual prevalence of IHNV in spawning adults is highly variable both within and between stocks. Laboratory studies confirm the persistence of IHNV in surviving Sockeye Salmon smolts (Müller et al., 2015), thus suggesting the infections detected in asymptomatic juvenile fish from the marine environment likely represent survivors from a naturally occurring IHNV exposure.

Preliminary results indicate that IHNV prevalence is highly variable among years in juvenile Sockeye Salmon caught in the Strait of Georgia and Discovery Islands ranging from 0% (2012, 2013 and 2015) to 10.5% (2014) across all stocks (Garver and Wade, 2017).

IHN disease has occurred in unvaccinated marine Atlantic Salmon farms in British Columbia in 1992, 2001 and 2012. There were significantly fewer disease management practices and biosecurity measures in place during the first two IHN epizootics (Garver and Wade, 2017). Additionally, diseased farms were not depopulated and therefore the 1992 and 2001 epizootics lasted for three to five years. IHNV was also confirmed on three Atlantic Salmon farms in 2012, two off the West Coast of Vancouver Island and one on the Sunshine Coast. All fish were eradicated from infected farms within a maximum of 12 days of the index cases being confirmed, and did not result in an epizootic. In all cases, the farms diagnosed with IHNV were not vaccinated against IHNV.

Atlantic Salmon are one of the most susceptible species to IHN disease, and based on laboratory studies, the lowest concentration of IHNV necessary to cause mortality in Atlantic Salmon exposed in seawater is 10^7 pfu/m^3 over a one hour exposure period (Garver et al., 2013). Sockeye Salmon, Rainbow Trout/steelhead trout and Chinook Salmon are also considered highly susceptible to IHN disease. For naïve juvenile Sockeye Salmon, the minimum lethal dose is estimated to vary from 10^8 to 10^9 pfu/m^3 for a one hour of exposure (i.e., 10 to 100 higher than that required to cause mortality in Atlantic Salmon) (Long et al., 2017). Coho Salmon (*O. kisutch*) and Pink Salmon (*O. gorbuscha*) can be infected by IHNV but are considered the least susceptible to IHN based on the absence of reports of natural outbreaks and low to no mortality in experimental studies. Other salmonids in which IHNV infection has been reported include Chum Salmon, Brook Trout (*Salvelinus fontinalis*), Brown Trout (*S. trutta*) and Lake Trout (*S. namaycush*) (reviewed in Garver and Wade (2017)).

In addition to differences in IHN disease susceptibility among species, variability in susceptibility may also exist at the stock level and can be dependent on the life stage at which exposure happens; Pacific salmon fry and juveniles are more susceptible to IHN disease than adults.

Once infected with IHNV, Atlantic Salmon shed increasingly higher quantities of virus as the disease progresses. Virus shedding peaks can average 3.2×10^7 pfu/fish/hr one to two days prior to death (Garver et al., 2013). Shed virus is only detected among those individuals that develop disease, suggesting that asymptomatic, disease-free Atlantic Salmon are not a significant source of virus (Garver et al., 2013). Both onset and progression of IHN is highly dependent on the exposure dose and therefore is likely to be highly variable between outbreaks (Garver et al., 2013).

Vaccination

A licenced commercial IHNV DNA vaccine (APEX-IHN®) has been available in Canada since July 2005. Two laboratory studies demonstrated its efficacy to protect Atlantic Salmon against IHN disease. In the first study, 17 months after APEX-IHN® vaccination, mortality in the vaccinated Atlantic Salmon reached 27% as compared to approximately 76% in the control group (Salonius et al., 2007). In the second study, five months after vaccination, mortality in the vaccinated Atlantic Salmon reached 2.7% as opposed to 96.7% in unvaccinated controls (Long et al., 2017). Additionally, disease transmission to naïve Sockeye Salmon was completely eliminated in vaccinated and IHNV infected Atlantic Salmon and reduced virus spread among cohabitating naïve Atlantic Salmon. Taken together, these results demonstrate that vaccination greatly reduces the infectious load and potential for IHNV transmission.

Characteristics of Fraser River Sockeye Salmon Stocks, Biology and Ecology

Grant et al. (2017) provide a review of the ecology and biology of the Fraser River Sockeye Salmon relevant in characterizing their interaction with Atlantic Salmon farms. The elements most relevant to inform the IHNV transfer risk assessment are summarized here.

Fraser River Sockeye Salmon exhibit two life-history types: lake-type and river-type. Lake-type Sockeye Salmon rear in a nursery lake for at least one year before migrating to the ocean, typically initiating the downstream migration to the Strait of Georgia between mid-April and late-May, with a peak in early May. River-type Sockeye Salmon migrate downstream to the Strait of Georgia shortly after gravel emergence, which for Harrison River Sockeye Salmon smolts are typically between early-June and late-July, with a peak in mid-July.

Once in the Strait of Georgia, lake-type juvenile Fraser River Sockeye Salmon tend to migrate through the Strait of Georgia and exit through the northern route migrating through the Discovery Islands. In 2014, juvenile Fraser River Sockeye Salmon have been caught in the Discovery Islands from mid-May to mid-July, with peak catches early-to-mid June (Neville et al., 2016). The residence time of juvenile Fraser River Sockeye Salmon in the Discovery Islands is estimated, based on tagging studies, swim speeds and distance, to range between 5 to 14 days (Grant et al., 2017).

Harrison River (river-type) Sockeye Salmon migrate out of the Strait of Georgia in the late-autumn and early-winter through either the northern or southern route. There are no estimates of residence time of Harrison River Sockeye Salmon juveniles in the Discovery Islands.

The migration patterns of juvenile Fraser River Sockeye Salmon through the Discovery Islands are not well characterized. Trawl surveys conducted in the Strait of Georgia caught juvenile Sockeye Salmon in the upper 45 m of the water column (Beamish et al., 2016), with the majority being caught in the upper 15 m, suggesting that juvenile Sockeye Salmon migrate in the same water depths as salmon farms. The proportion of the population that migrates past salmon farms in the Discovery Islands is unknown. Juvenile Fraser River Sockeye Salmon have been observed in the vicinity of salmon farms in this region.

Adult Sockeye Salmon return to the Fraser River via either the northern route or the southern route, with proportion that divert through Johnstone Strait ranging from 10 to 96% (Grant et al., 2017). In-season test fishery data indicate that Sockeye Salmon are present in the Discovery Islands from at least mid-July to the beginning of September. Based on arrival timing at Mission, average swimming speed, and distance, and no additional residence time in the Strait of Georgia, it is estimated that adult Sockeye Salmon could be in the Discovery Islands from late-June to early-October. Based on these estimates, adult Fraser River Sockeye Salmon could spend approximately three days swimming through the Discovery Islands.

Adult Fraser River Sockeye Salmon return abundances are highly variable, and have ranged from 1.5 to 28.2 million between 1980 and 2014 (Grant et al., 2017). Factors contributing to this high variability include the cyclic nature of some stocks which produce large returns once every four years, the variability in brood year spawner abundances and the survival from egg to adult return stages. Marine survival data are not available for most Fraser River Sockeye Salmon stocks; however, there are data available from 1951 to 2013 for Chilko Lake Sockeye Salmon. The average Chilko Lake Sockeye Salmon marine survival from the outlet of Chilko Lake to returning adult over the whole time series is 6.9% but has decreased in recent years to 4.3% (1992 from 2013 ocean entry years) (Grant et al., 2017).

Pacific salmon diversity has been defined using Conservation Units which are based on the life-history, ecology, and genetics of the populations. Conservation Units are considered to be a fundamental unit of biodiversity under DFO's Wild Salmon Policy, which further defines a Conservation Unit as "a group of wild salmon sufficiently isolated from other groups that, if extirpated is very unlikely to recolonize naturally within an acceptable timeframe, such as a human lifetime or a specified number of salmon generations" (DFO, 2005). There are currently 24 Fraser River Sockeye Salmon Conservation Units, 22 are lake-type and two are river-type. Of the 24 Conservation Units, 11 are a conservation concern.

IHNV Transfer Risk Assessment

Mimeault et al. (2017) provide the complete assessment of the risk to Fraser River Sockeye Salmon due to IHNV attributable to Atlantic Salmon farms in the Discovery Islands of British Columbia. The elements most relevant to inform the IHNV transfer risk assessment are summarized here.

The risks to Fraser River Sockeye Salmon abundance and diversity due to IHNV transfer from Atlantic Salmon farms operating in the Discovery Islands have been assessed under current fish health management practices.

Conceptual model

The risk assessment followed three main steps outlined in Figure 7, which included the likelihood assessment, consequence assessment and estimation of risk.

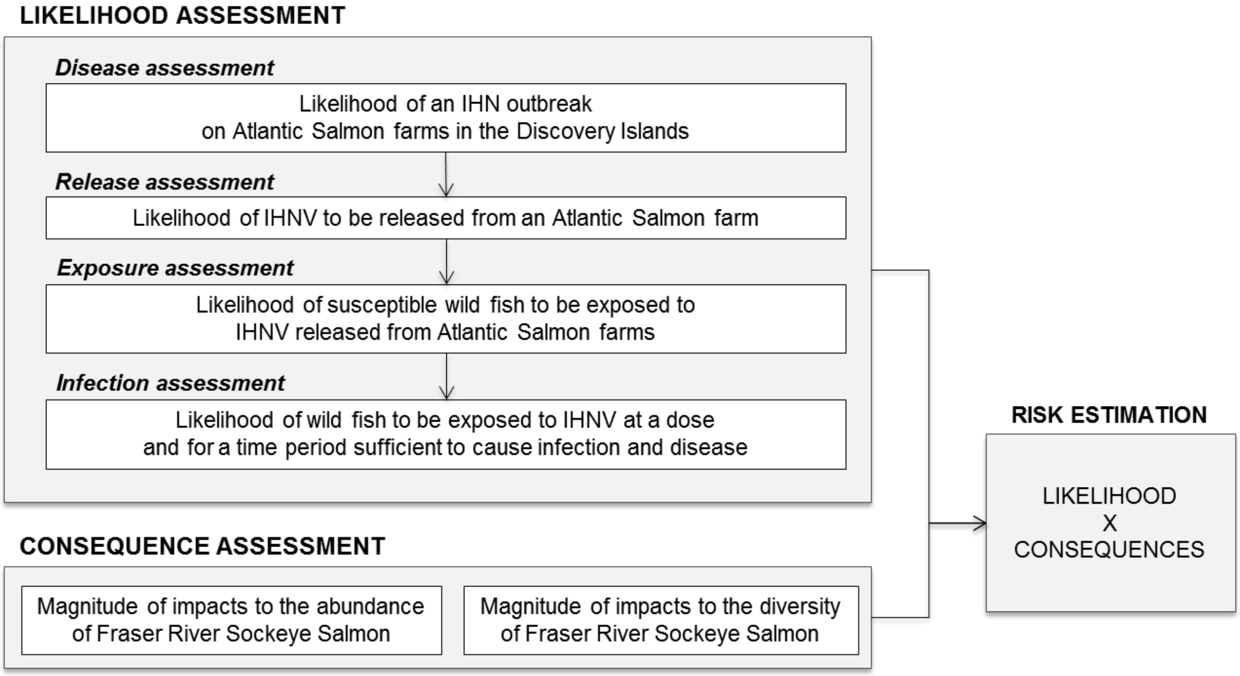

Figure 7. Conceptual model for risk assessment of IHNV attributable to Atlantic Salmon farms located in the Discovery Islands, BC.

Likelihood assessment

This section determined the likelihood that wild fish populations would be infected and diseased due to IHNV released from Atlantic Salmon farms operating in the Discovery Islands under current fish health management practices. The likelihood assessment was conducted through four sequential assessments: disease, release, exposure and infection assessments. Main considerations and conclusions are reported here.

Disease assessment

While IHNV is endemic to BC and Atlantic Salmon farms in the Discovery Islands have previously had epizootics and isolated outbreaks in unvaccinated fish, the current fish health management practices include both regulatory biosecurity and fish health management practices, as well as additional voluntary practices such as vaccination against IHN. Taken together, it was concluded with **reasonable certainty** that it is **very unlikely** that an IHN outbreak will occur on Atlantic Salmon farms in the Discovery Islands under the current fish health management practices.

Release assessment

Notwithstanding the likelihood from the disease assessment, the release assessment determined the likelihood of IHNV to be released from an IHN-positive Atlantic Salmon farm operating in the Discovery Islands into an environment accessible to wild populations of Fraser River Sockeye Salmon or other susceptible fish. Three potential release pathways were considered: farmed Atlantic Salmon, mechanical vectors (e.g., personnel, visitors, wildlife), and fomites (e.g., farm equipment and vessels).

Since Atlantic Salmon showing clinical signs of disease shed IHNV into the surrounding environment and given that Atlantic Salmon are reared in net pens, it was concluded with **high certainty** that the likelihood of release into the environment from infected Atlantic Salmon is **expected**.

Considering the protocols for handling and storing dead fish, labeling, cleaning, disinfecting and storing gear, biosecurity requirements for visitors, and restrictions on vessel and personnel movements in the event of a confirmed case of IHN, neither the likelihood of release through mechanical vectors nor fomites were expected to be of significant concern.

Exposure assessment

The exposure assessment determined the likelihood that a susceptible fish would be exposed to IHNV released from Atlantic Salmon farms operating in the Discovery Islands. Exposure was defined as one fish encountering a single viral particle released from any of the Atlantic Salmon farms operating in the Discovery Islands.

Three potential exposure groups were considered: juvenile Fraser River Sockeye Salmon, adult Fraser River Sockeye Salmon and other IHN susceptible species occurring in the Discovery Islands (to address potential ecological consequences through prey, predator or competitor interactions). For each exposure group, two potential exposure routes were considered: in net pens and in viral plumes dispersed from Atlantic Salmon farms.

The exposure assessment was a comparison of the temporal and spatial occurrence of IHNV released from Atlantic Salmon farms and exposure groups in the Discovery Islands.

Suspected index cases of IHN outbreaks in Discovery Islands occurred in July (epizootic from 1992 to 1997) and August (epizootic from 2001 to 2003). Every year millions of juvenile Fraser River Sockeye Salmon migrate through the Discovery Islands from approximately mid-May to mid-July. Consequently, there is potential for temporal overlap between IHNV released from infected Atlantic Salmon farms and juvenile Fraser River Sockeye Salmon in the Discovery Islands.

During previous IHN epizootics and outbreaks, at any given time, the disease was present only in a subset of active farms. Atlantic Salmon farms operating in the Discovery Islands occupy an extremely small area and volume of the overall region and a relatively small area even in the narrowest channel of the Discovery Islands in which Atlantic Salmon farms are operating. The above are factors limiting the likelihood of wild fish to encounter an infected farm. However, although rapidly inactivated by sunlight and biota, IHNV can survive in seawater. IHNV introduced into the marine environment can be transported horizontally and mixed vertically due to the currents in the region. Waterborne dispersal of IHNV has been suggested to play a role in the spread of the disease between fish farms and corroborated by hydrodynamic modelling in the Discovery Islands. Modelling of IHNV dispersal in the surface of the water column suggests that IHNV plumes will extend beyond the limit of the farms and sometimes even cover the entire width of channels. Consequently, there is potential for spatial overlap between IHNV released from infected Atlantic Salmon farms and juvenile Fraser River Sockeye Salmon in the Discovery Islands.

It was therefore concluded with **reasonable uncertainty** that the likelihood for at least one juvenile Fraser River Sockeye Salmon to be exposed to at least one particle of IHNV in the net pen of an Atlantic Salmon farm in the Discovery Islands is **likely**. It was also concluded with **reasonable certainty** that the likelihood for juvenile Fraser River Sockeye Salmon to be exposed to IHNV through a dispersion plume from an Atlantic Salmon farm in the Discovery Islands is **very likely**.

Temporal and spatial occurrence of adult Fraser River Sockeye Salmon and other IHN susceptible fish species (Chinook and Chum Salmon) were also considered and are reported in Table 1.

Infection assessment

The infection assessment determined the likelihood that susceptible wild fish would be exposed to IHNV at a dose and for a period of time sufficient to cause infection and disease. The infection assessment assumed that susceptible fish have been exposed to IHNV released from a farm.

The potential maximum infection pressure in an Atlantic Salmon net pen during an IHN outbreak was estimated through a compartmental epidemiological Susceptible, Exposed, Infected, Recovered (SEIR) model (refer to Mimeault et al. (2017) for more details). The simulation assumed that all farmed Atlantic Salmon were vaccinated against IHNV with a 95% vaccine efficacy. Results suggest that there would be no spread of the infection within the farm under these conditions. Consequently, no IHN outbreak is expected on an Atlantic Salmon farm vaccinated against IHN disease with the vaccine having 95% efficacy. The maximum number of infected Atlantic Salmon would therefore be the same as the number of initially infected ones.

Under the current fish health practices and using laboratory-derived IHNV shedding rates in Atlantic Salmon (3.2×10^7 pfu per fish per hour) (Garver et al., 2013), the maximum IHNV concentration in net pens was estimated to be 1.4×10^4 pfu/m^3 which is approximately 7,000 times lower than the minimum lethal one-hour dose of 108 to 109 pfu/m^3 for juvenile Sockeye Salmon. Refer to Mimeault et al. (2017) for more details on these estimations of IHNV concentrations.

The maximum IHNV concentration in waters surrounding Atlantic Salmon farms in the Discovery Islands during an IHN outbreak in April and July was simulated by coupling the FVCOM with an existing IHNV dispersion, inactivation and re-infection model which accounts for dispersal and viral decay (Foreman et al., 2015a). When all active Atlantic Salmon farms released viral particles simultaneously (Figure 8), the model estimated the maximum IHNV concentration in plumes dispersed from the farms to be 8.7×10^2 pfu/m^3 which is approximately 100,000 times lower than the minimum lethal one-hour dose of 10^8 to 10^9 pfu/m^3 for juvenile Sockeye Salmon.

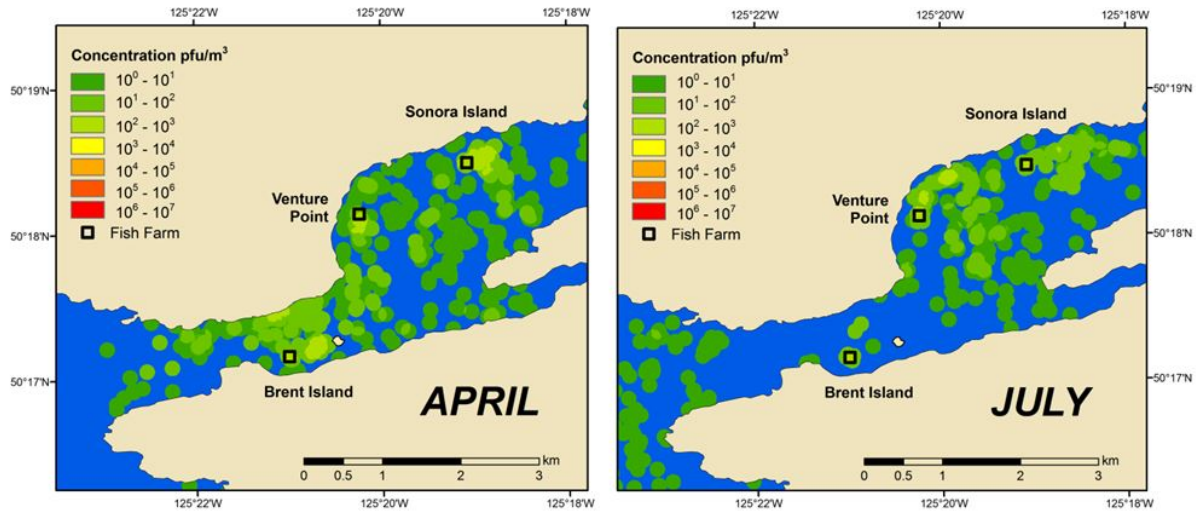

Figure 8. Maximum modelled distribution and concentration of IHNV particles released after over 300 hours of continuous shedding from infected Atlantic Salmon farms in April (left panel) and July (right panel), highlighting three farms in the Okisollo Channel. The model assumes all Atlantic Salmon are vaccinated with 95% efficacy. All modelled concentrations (upper 5 m) are under 10^3pfu/m^3.

It was therefore concluded with **reasonable uncertainty** that the likelihood for juvenile Fraser River Sockeye Salmon to be exposed to IHNV released from Atlantic Salmon farms at a dose and for a period of time sufficient to cause infection and disease is **extremely unlikely** both in net pens and in dispersed viral plumes.

The likelihood for adult Fraser River Sockeye Salmon, which are less susceptible to IHNV than juvenile Sockeye Salmon and other IHN susceptible fish species (Chinook and Chum Salmon) to become infected and diseased were assessed and are summarized in Table 1.

Overall likelihood

The overall likelihood of juvenile Fraser River Sockeye Salmon to become infected and diseased by IHNV attributable to Atlantic Salmon farms in the Discovery Islands depended on the sequential likelihoods of disease, release, exposure and infection and was consequently determined to be **extremely unlikely** with **reasonable uncertainty**. The lack of knowledge on the precise residence time and occurrence of juvenile Sockeye Salmon around Atlantic Salmon farms and the impact of exposure to IHNV at concentrations lower than the minimal infectious lethal dose contributed to the uncertainty associated to the overall likelihood assessment.

The risk assessment also included adult Fraser River Sockeye Salmon and other IHN susceptible fish species (Chinook and Chum Salmon) and their likelihood of becoming infected and diseased by IHNV attributable to Atlantic Salmon farms in the Discovery Islands was determined separately to be **extremely unlikely** with **reasonable certainty**.

Table 1 is a summary of the estimated likelihoods and uncertainties for each step of the likelihood assessment. The overall likelihood of wild fish populations to become infected and diseased by IHNV attributable to Atlantic Salmon farms in the Discovery Islands was determined to be **extremely unlikely** with **reasonable uncertainty**. Refer to Mimeault et al. (2017) for more details on the combination of likelihood rankings.

Table 1. Summary of likelihood and uncertainty estimates for each step of the likelihood assessment. Estimates are reported in white cells and likelihood combination results are reported in tan cells. Combined and overall likelihoods were determined using accepted methodologies in qualitative risk assessments adopting the lowest value for dependent events and the highest value for independent events.

Disease assessment	**Likelihood of disease**	Very unlikely *Reasonable certainty*					
Release assessment	**Release pathways**	**Farmed Atlantic Salmon**		**Mechanical vectors**		**Fomites**	
	Likelihood of release	Expected *High certainty*		Very unlikely *High certainty*		Very unlikely *High certainty*	
	Combined likelihood of release	Expected *High certainty*					
Exposure and infection assessments	**Exposure group**	**Juvenile Fraser River Sockeye Salmon**		**Adult Fraser River Sockeye Salmon**		**Other IHN susceptible fish**	
	Exposure route	**In net pens**	**In plumes**	**In net pens**	**In plumes**	**In net pens**	**In plumes**
	Likelihood of exposure	Likely *Reasonable uncertainty*	Very likely *Reasonable certainty*	Extremely unlikely *Reasonable certainty*	Very likely *Reasonable certainty*	Likely *Reasonable certainty*	Very likely *Reasonable certainty*
	Likelihood of infection	Extremely unlikely *Reasonable uncertainty*	Extremely unlikely *Reasonable uncertainty*	Extremely unlikely *Reasonable certainty*	Extremely unlikely *Reasonable certainty*	Extremely unlikely *Reasonable certainty*	Extremely unlikely *Reasonable certainty*
Combined likelihoods for each exposure route in a given exposure group		Extremely unlikely *Reasonable uncertainty*	Extremely unlikely *Reasonable uncertainty*	Extremely unlikely *Reasonable certainty*	Extremely unlikely *Reasonable certainty*	Extremely unlikely *Reasonable certainty*	Extremely unlikely *Reasonable certainty*
Combined likelihoods for each exposure group		Extremely unlikely *Reasonable uncertainty*		Extremely unlikely *Reasonable certainty*		Extremely unlikely *Reasonable certainty*	
Overall likelihood of disease, release, exposure and infection		Extremely unlikely *Reasonable uncertainty*					

Consequence assessment

The consequence assessment determined the potential magnitude of impact of IHNV attributable to Atlantic Salmon farms on the abundance and diversity of Fraser River Sockeye Salmon, assuming that wild fish populations have been exposed to IHNV. The potential impacts from the exposure of juvenile Fraser River Sockeye Salmon, adult Fraser River Sockeye Salmon and other IHN susceptible species (Chinook and Chum Salmon) were examined separately.

Juvenile Fraser River Sockeye Salmon, being the exposure group most susceptible to IHN, were concluded to be the only exposure group through which potential consequences to the abundance and diversity of Fraser River Sockeye Salmon could arise as a result of IHNV infection attributable to Atlantic Salmon farms.

No natural IHN mortality events have been observed in the marine environment and adult life stages of Sockeye Salmon. Laboratory exposures of post-smolt Sockeye Salmon have been conducted and reported mortality rates ranging from 0 to 12.5% (Traxler et al., 1993; Long et al., 2017). However, mortality rates associated with natural freshwater IHNV epizootics in smolts were considered to more closely reflect field conditions rather than a laboratory setting.

IHN epizootics have occurred in 1.5-year-old Sockeye Salmon smolts in Alaska in two consecutive years in 1980 and 1981. The estimated mortality rates based on observed moribund and dead fish ranged between 2.5 and 8.0% (Burke and Grischkowsky, 1984) in the last proportion of out-migrating smolts. These reported mortalities were used as a proxy for juvenile Sockeye Salmon mortality due to IHN exposure in seawater.

Abundance

The potential consequence categories to the abundance of returning adult Fraser River Sockeye Salmon were defined prior to the risk assessment as ranging from negligible (up to a 1% reduction) through to extreme (over 50% reduction). Using the proxy mortality rates from the outbreak in out-migrating smolts (2.5 to 8%) as the potential reduction in the population associated with IHNV infection and disease attributable to Atlantic Salmon farms, it was concluded with **high uncertainty** that the potential magnitude of consequences to the abundance of Fraser River Sockeye Salmon resulting from IHNV infection attributable to Atlantic Salmon farms would be **moderate** (between 5 and 10% reduction in the number of returning adult Fraser River Sockeye Salmon). The lack of information on population effects of IHN resulting from exposure in seawater accounted for the high uncertainty associated with this assessment.

Diversity

The consequence to diversity was assessed against predicted reductions in abundance of conservation units and whether or not that reduction for either cyclic or non-cyclic stocks would result in the loss of a conservation unit. Given an estimated range of 2.5 to 8% mortality from IHN in seawater, this reduction in abundance in any given year would be compensated in other years in both cyclic and non-cyclic Fraser River Sockeye Salmon stocks. Consequently, it was concluded with **high uncertainty** that the potential magnitude of consequences to the diversity of Fraser River Sockeye Salmon resulting from IHNV infection attributable to Atlantic Salmon farms would be **moderate** (i.e., moderate reduction in abundance in some conservation units that would not result in the loss of a Fraser River Sockeye Salmon conservation unit). The lack of information on population effects of IHN resulting from exposure in seawater accounted for the high uncertainty associated with this assessment.

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 and used the predetermined risk matrices (Figure 9 and Figure 10).

Under the current fish health management practices, the risk to the abundance and diversity of Fraser River Sockeye Salmon as a result of IHNV infection attributable to Atlantic Salmon farms operating in the Discovery Islands were both determined to be **minimal**.

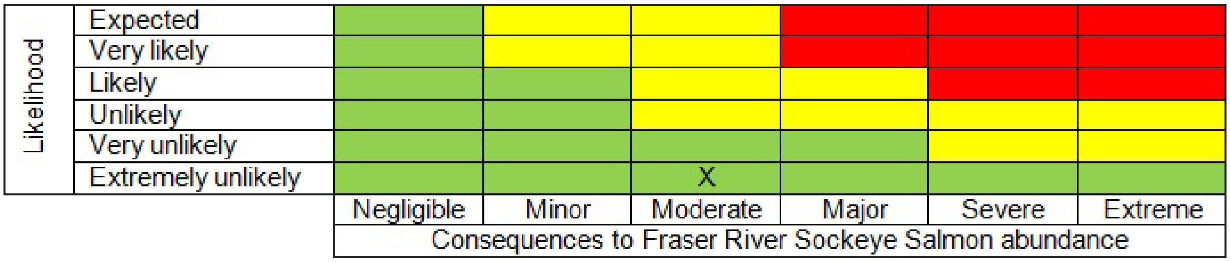

Figure 9. Risk matrix for combining the results of the likelihood and consequence to Fraser River Sockeye Salmon abundance assessments in which green, yellow and red, respectively, represent minimal, moderate and high risks. The X indicate the outcome of the analysis.

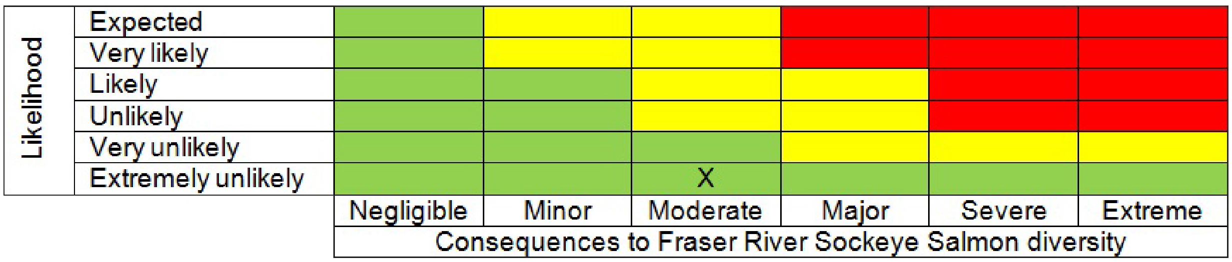

Figure 10. Risk matrix for combining the outputs of the likelihood and consequence to Fraser River Sockeye Salmon diversity assessments in which green, yellow and red, respectively, represent minimal, moderate and high risks. The X indicate the outcome of the analysis.

Sources of uncertainty

Uncertainty remains both in 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

Uncertainties associated to the rankings in the likelihood assessment were generally lower in the first steps (i.e., high certainty) and higher in the last steps (i.e., reasonable uncertainty).

The reasonable certainty level associated with the disease assessment resulted from the low levels of operational deficiencies that could affect fish health on Atlantic Salmon farms in the Discovery Islands; the adoption and implementation of the Viral Management Plan by all companies operating in the Discovery Islands; and the BAP certification of all Atlantic Salmon farms in the Discovery Islands providing confidence that vaccination for IHNV is being implemented. However, the voluntary nature of some key fish health management practices prevented the attribution of a high certainty level for the disease assessment.

The high certainty level associated with the release assessment resulted from available peer-reviewed and published data on shedding of IHNV from disease Atlantic Salmon.

The reasonable uncertainty associated to the exposure of juvenile Fraser River Sockeye Salmon in net pens results from the lack of knowledge of the precise residence time of juvenile Fraser River Sockeye Salmon in the Discovery Islands and occurrence around Atlantic Salmon farms.

The reasonable uncertainty associated with the infection of juvenile Fraser River Sockeye Salmon results from the need to model the estimated infection pressure and the lack of knowledge of the impact of exposure to waterborne IHNV concentrations lower than the minimal infectious lethal dose.

Uncertainties in the consequence assessment

The high uncertainties in the consequence assessments for both abundance and diversity result from the absence of data on IHN mortality in wild Sockeye Salmon exposed to IHNV in seawater and the high reliance on proxy data and information; the lack of knowledge of potential sub-lethal and cumulative effects of exposure to IHNV; and the intrinsic complexity and high variability of Sockeye Salmon marine survival. There are additional uncertainties related to the natural environmental variability, including climate change, which influence viral survival in seawater and distribution, salmon migration patterns and timing, etc.

CONCLUSIONS

Oceanographic and Environmental Conditions of the Discovery Islands

The Discovery Islands are a complex network of islands, narrow channels and deep fjords with water properties that vary significantly in time, location and depth. Oceanographic conditions in this region vary both seasonally and regionally, with a monthly average temperature range of 6 to 14ºC (recorded minimum and maximum of 3 and 24ºC), monthly average salinity range between 23 and 31 (minimum and maximum of 2 and 32) and monthly average levels of dissolved oxygen ranging between 170 and 340 mmol/m^3 (minimum and maximum of 50 and 550 mmol/m^3). UV is observed to vary seasonally, and is reduced during periods of cloudiness and at night. Measurements show that the intensity of UV is reduced exponentially with depth to less than one percent of its surface value within 10 m.

Water currents in the Discovery Islands are comprised of three components, each with different time scales: tidal streams, buoyancy currents and wind-driven currents. Tidal streams affect hourly to daily water currents with flood and ebb tides coming in different directions and sometimes having different speeds; buoyancy currents which are predominantly driven by freshwater input; and wind-driven currents whereby wind stress directly forces surface water momentum which in turn, is transmitted further down the water column by mixing and viscosity. Though tidal currents generally move particles back and forth with little net transport, in regions like Discovery Passage where these currents are much stronger than the other components, movement during ebb or flood phases can result in a net transport to different regions like the northern Strait of Georgia. However, in most regions, the primary current components that move pathogens and other particulate matter significant distances are the buoyancy and wind-driven flows. The magnitude of these currents and the distances they move particles vary both spatially and temporally.

Hydrodynamic and particle tracking models have been developed to respectively simulate the circulation of the Discovery Islands and the dispersal of particles from fish farms. FVCOM accuracy has been evaluated against available observations and the particle tracking model results were used to estimate pathogen inactivation and dispersion from Atlantic Salmon farms. The time scales for passive particle dispersion vary by season, consistent with the associated forcing fields.

British Columbia Farmed Atlantic Salmon Health Management Practices

Current farmed Atlantic Salmon fish health management practices include both regulatory requirements and voluntary practices, as well as oversight by the regulator. In addition, all Atlantic Salmon farms in the Discovery Islands are certified through Best Aquaculture Practices Certification (BAP).

There are three Atlantic Salmon farming companies operating marine farms in the Discovery Islands: Cermaq Canada, Grieg Seafood and Marine Harvest Canada. Under the Pacific Aquaculture Regulations, as a condition of licence, each company has a Salmonid Health Management Plan (SHMP) and accompanying proprietary Standard Operating Procedures (SOPs). These SOPs along with other conditions of licence provide evidence of biosecurity measures in place to mitigate disease events and minimize spread of pathogens within and away from a farm should they occur. Compliance with these practices is audited by the Department of Fisheries and Oceans as a condition of licence.

Through DFO's audit program, tissue samples are taken for routine pathogen screening at accredited laboratories. These results are compared to the mandatory reporting requirements made by each company as a condition of licence. In addition, the companies monitor the health of their fish through the collection and analysis of syndromic information and collect samples for pathogen screening. Increases in mortalities must be reported to DFO as a condition of licence, and suspicions or detection of reportable diseases must be reported to DFO and CFIA.

Vaccination of Atlantic Salmon is not a requirement of licence; however, all companies do voluntarily vaccinate their fish for many pathogens including IHNV. The agreement to vaccinate fish and have a coordinated effort in mitigation of disease and response in an outbreak situation is formalized in a Memorandum of Understanding termed the Salmon Farming Industry Viral Disease Management Plan. The use of vaccines was mentioned in the first version of the Viral Management Plan ratified in 2011 and indicated that vaccines were to be used in common areas. Since 2015, the IHNV vaccine has been used by all companies on all smolt before sea water entry. Vaccination against IHNV is also a requirement of the BAP.

Characterization of Infectious Hematopoietic Necrosis Virus (IHNV)

IHNV is endemic to British Columbia where it has been detected in freshwater and marine life stages of wild Sockeye Salmon as well as in marine cultured Atlantic Salmon. Atlantic Salmon post smolts are 10 to 100 times more susceptible to IHN disease than the native Sockeye Salmon at a similar life stage. While Atlantic Salmon remain highly susceptible to IHNV, Sockeye Salmon become resistant to IHN disease with increasing age.

Atlantic Salmon with acute IHN disease can shed virus with levels peaking one to two days prior to the death of the animal. Once shed into the marine environment, the infectiousness of IHNV declines due to inactivation by exposure to sunlight and natural biota present in the seawater. Consequently, IHNV has an abbreviated lifespan whereby it can infect another host.

The APEX-IHN® vaccine is highly efficacious and reduces the infectious load and potential for IHNV transmission. Since its licensure, there has been no detection of IHNV in an APEX-IHN® vaccinated farmed Atlantic Salmon.

Characteristics of Fraser River Sockeye Salmon Stocks, Biology and Ecology

Most juvenile Sockeye Salmon smolts exit the Fraser River between mid-April and late-May with a peak in early-May. Lake-type Fraser River Sockeye Salmon have been found in the Strait of Georgia until August and tend to exit the Strait of Georgia through the northern route, through the Discovery Islands. The amount of time an average juvenile lake-type Sockeye Salmon spends migrating through the Strait of Georgia has been estimated to be between 20 and 59 days. In recent years, juvenile Fraser River Sockeye Salmon have been caught in the Discovery Islands from mid-May to mid-July, with peak catches in early-to-mid June. The residence time of juvenile Fraser River Sockeye Salmon in the Discovery Islands is estimated to range between 5 and 14 days.

River-type Harrison River Sockeye Salmon smolts exit the Fraser River between early-June and late-July with a peak in mid-July. Juvenile Harrison River Sockeye Salmon migrate out of the Strait of Georgia in the late-autumn and early-winter through either the northern or southern route. There are no estimates of residence time of Harrison River Sockeye Salmon juveniles in the Discovery Islands.

Adult Sockeye Salmon return to the Fraser River via both the northern route and southern route. The proportion that divert through Johnstone Strait in recent years has averaged 52%. In season test fishery data show that Sockeye Salmon are present in the Discovery Islands from at least mid-July to the beginning of September. Back calculations based on swimming speed and arrival time at Mission estimate that adult Sockeye Salmon could be in the Discovery Islands from late-June to early-October assuming no residence time in the Strait of Georgia. Based on these same estimates, Fraser River Sockeye Salmon could spend approximately three days swimming through the Discovery Islands.

Adult Fraser River Sockeye Salmon return abundances are highly variable, and have ranged from 2 to 28 million between 1980 and 2014. Marine survival data are not available for most Fraser River Sockeye Salmon stocks; however, there is a long-term data set from 1951-2013 available for Chilko Lake Sockeye Salmon which has had an average marine survival from the outlet of Chilko Late to returning adult of 6.9%, although more recently this has decreased to 4.3% (1992-2013).

IHNV Transfer Risk Assessment

The assessment concluded that IHNV attributable to Atlantic Salmon farms in the Discovery Islands pose minimal risks to Fraser River Sockeye Salmon abundance and diversity under the current fish health management practices.

There are two main factors driving the minimal level of risk. First, IHN outbreaks on Atlantic Salmon farms in the Discovery Islands are very unlikely to occur (reasonable certainty) given current health management practices by salmon companies including highly efficient vaccination against IHN disease. Second, even assuming exposure to IHNV, the number of susceptible fish on an Atlantic Salmon farm is low due to the use of vaccination. In addition, established biosecurity measures, on-going fish health surveillance on farms, and disease response protocols, including depopulation, contribute to limit the potential for release and spread of IHNV from Atlantic Salmon farms. The maximum IHNV waterborne concentrations on and surrounding infected farms were consequently estimated to remain below the IHNV minimum lethal dose for juvenile Sockeye Salmon. It is therefore extremely unlikely (reasonable uncertainty) that juvenile Sockeye Salmon (the most susceptible exposure group) would become infected and diseased.

There are several sources of uncertainty, both due to intrinsic variability and lack of knowledge, associated with the determination of the risk to Fraser River Sockeye Salmon due to IHNV transfer from Atlantic Salmon farms in the Discovery Islands. Main uncertainties are related to the residence time of susceptible species on and near Atlantic Salmon farms in the Discovery Islands; the IHNV waterborne concentrations during an IHN outbreak; the sub-lethal effects of exposure to IHNV at concentrations lower than the minimum lethal dose; the impacts of juvenile and adult exposure to IHNV in seawater; the complexity of marine survival; and potential cumulative effects. Overall, the highest level of uncertainty was related to the magnitude of consequences on Fraser River Sockeye Salmon.

OTHER CONSIDERATIONS

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

SOURCES OF INFORMATION

This Science Advisory Report is from the December 5-8, 2016 National Peer Review Meeting on Assessment of the risk to Fraser River sockeye salmon due to Infectious Hematopoietic Necrosis Virus transfer from Atlantic salmon farms located in the Discovery Islands, British Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Beamish, R. J., Neville, C. M., Sweeting, R. M., Beacham, T. D., Wade, J. and Li, L. 2016. Early ocean life history of Harrison River sockeye salmon and their contribution to the biodiversity of sockeye salmon in the Fraser River, British Columbia, Canada. Trans. Am. Fish. Soc. 145(2): 348-362.

Bootland, L. M. and Leong, J.-A. C. 1999. Infectious haematopoietic necrosis virus. *In* Fish Diseases and Disorders. Woo, P. T. K. and Bruno, D. W. (eds.). 2nd ed. CAB International. 3: pp 57-121.

Burke, J. and Grischkowsky, R. 1984. An epizootic caused by infectious haematopoietic necrosis virus in an enhanced population of sockeye salmon, *Oncorhynchus nerka* (Walbaum), smolts at Hidden Creek, Alaska. J. Fish Dis. 7(5): 421-429.

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

Cohen, B. I. 2012. Recommendations, summary, process. The Uncertain Future of Fraser River Sockeye. Vol. 3. Minister of Public Works and Government Services Canada, Publishing and Depository Services, Public Works and Government Services Canada, Ottawa, ON K1A 0S5. 211 p.

DFO. 2005. Canada's policy for conservation of wild Pacific salmon. Fisheries and Oceans Canada. 49 p.

DFO. 2010. Pathways of effects for finfish and shellfish aquaculture. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/071. 22 p.

Dixon, P., Paley, R., Alegria-Moran, R. and Oidtmann, B. 2016. Epidemiological characteristics of infectious hematopoietic necrosis virus (IHNV): a review. Vet. Res. 47: 63.

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

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

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

Garver, K. A., Mahony, A. A. M., Stucchi, D., Richard, J., Van Woensel, C. and Foreman, M. 2013. 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. and Wade, J. 2017. Characterization of Infectious Hematopoietic Necrosis Virus (IHNV). DFO Can. Sci. Advis. Sec. Res. Doc. 2017/073. vi + 32 p.

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

Grant, S. C. H., Holt, C., Wade, J., Mimeault, C., Burgetz, I. J., Johnson, S. and Trudel, M. 2017. 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 (in review)

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

Lin, Y., Jiang, J., Fissel, D. B., Foreman, M. G. and Willis, P. G. 2011. Application of finite-volume coastal ocean model in studying strong tidal currents in Discovery Passage, British Columbia, Canada. Estuar. Coast. Model. 1: 99-117.

Long, A., Richard, J., Hawley, L., LaPatra, S. E. and Garver, K. A. 2017. Transmission potential of infectious hematopoietic necrosis virus in APEX-IHN® vaccinated Atlantic salmon. Dis. Aquat. Org. 122: 213-221.

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.

Müller, A., Sutherland, B. J. G., Koop, B. F., Johnson, S. C. and Garver, K. A. 2015. Infectious hematopoietic necrosis virus (IHNV) persistence in sockeye salmon: effect on brain transcriptome and response to the viral mimic poly(I:C). BMC Genomics 2015 16(634): 1-19.

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.

Saksida, S. M. 2006. Infectious haematopoietic necrosis epidemic (2001 to 2003) in farmed Atlantic salmon *Salmo salar* in British Columbia. Dis. Aquat. Org. 72: 213-223.

Salonius, K., Simard, N., Harland, R. and Ulmer, J. B. 2007. The road to licensure of a DNA vaccine. Curr. Opin. Investig. D. 8(8): 635-641.

St-Hilaire, S., Ribble, C. S., Stephen, C., Anderson, E., Kurath, G. and Kent, M. L. 2002. Epidemiological investigation of infectious hematopoietic necrosis virus in salt water net-pen reared Atlantic salmon in British Columbia, Canada. Aquaculture 212: 49-67.

Thomson, R. E. 1981. Oceanography of the British Columbia coast. Can. Spec. Publ. Fish. Aquat. Sci. 56: 291 p.

Traxler, G. S., Roome, J. R. and Kent, M. L. 1993. Transmission of infectious hematopoietic necrosis virus in seawater. Dis. Aquat. Org. 16: 111-114.

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 + 58 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. 2017. Advice from the 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 area, British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2017/048.

Aussi disponible en français :

MPO. 2017. Avis tiré de l'évaluation du risque pour le saumon rouge du fleuve Fraser que représente le transfert du virus de la nécrose hématopoïétique infectieuse à partir des fermes de saumon atlantique situées dans la région des îles Discovery (Colombie-Britannique). Secr. can. de consult. sci. du MPO, Avis sci. 2017/048.