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Physical containment approaches to mitigate potential escape of European-origin Atlantic salmon in south coast Newfoundland aquaculture operations

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Foreword

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

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ABSTRACT

Escapes from aquaculture operations affect the fish farm operator through a loss of potential profits and negative public perception that can generally affect the marketability of farm raised products. Land-based freshwater production hatcheries are essential to the grow-out cycle but are not entirely free of escapes. The vast majority of escapes occur from marine fish farm installations that experience energy on a continual basis from ocean surface currents, wind-driven waves that frequently occur but with higher energy during storms, and tidal currents that affect all aspects of the deployed farm infrastructure regardless of depth. Escapes from marine Atlantic salmon aquaculture operations may occur following structural failures of the net pen and mooring components, operational/management failures during routine fish handling and farm management procedures, and biological failures that include successful predator attacks and vandalism. The first line of defence to minimize any negative effects due to escapes must include all feasible mitigation strategies to prevent the occurrence of escape from the farm operation. Evaluating specific mitigation measures to calculate return on investment to mitigate risks is difficult as often many of these measures cannot be isolated within the very integrated fish farming system. However, specific mitigation measures may be more broadly presented within a short list of high level recommendations including:

- Consideration should be given to whether Codes of Containment should become mandatory within jurisdictional legislation and a condition of the appropriate approval to operate or the aquaculture license. Furthermore, regulatory departments should consider developing an industry standard similar to the Norwegian standard for marine fish farms given the compelling evidence that implementation of the Norwegian standard has resulted in a dramatic decrease in total fish farm escapes throughout its aquaculture sector.
- All existing and potential freshwater and saltwater Atlantic salmon aquaculture sites should be extensively surveyed to collect pertinent information that may contribute to escapes from the operations.
- Selection of appropriate equipment should involve a professional engineer to properly design and dimension all components for the collected site specific data prior to installation of Atlantic salmon fish farms. Deployed equipment should be regularly audited for compliance with the engineered design to ensure proper maintenance continues during use.
- All equipment and operations implemented should include aspects of redundancy, fail-safe design and safety margins for the specific environment to increase the likelihood for full containment of the Atlantic salmon stock throughout the grow-out cycle.
- All operators should ensure that its entire staff is properly trained and understand all standard operating procedures to operate required equipment and facilitate necessary fish handling and farm operations to mitigate fish farm escapes.
- Finally, the Atlantic salmon industry generally remains an innovative sector and this attitude should continue with regards to escape mitigation and might include aspects associated with new equipment (e.g., net pen design, new net materials) and handling procedures.

Méthodes de confinement physique visant à réduire les échappées potentielles de saumon de l’Atlantique d'origine européenne dans le cadre des opérations aquacoles menées dans la côte sud de Terre-Neuve

RÉSUMÉ

Les échappées qui surviennent pendant les opérations aquacoles ont un impact sur l'exploitant de pisciculture, car elles peuvent entraîner une perte de profits et suscitent chez la population une perception négative, ce qui a généralement des répercussions sur l'attrait commercial des produits d'élevage. Les écloseries terrestres de production en eau douce sont essentielles au cycle de grossissement. Or, elles ne sont pas parfaitement prémunies contre les échappées. La vaste majorité des échappées surviennent dans les piscicultures marines qui reçoivent continuellement de l'énergie issue des courants océaniques de surface, des vagues générées par le vent qui déferlent souvent, qui engendrent encore plus d'énergie pendant les tempêtes, et des courants de marée qui ont une incidence sur l'ensemble des caractéristiques de l'infrastructure piscicole exploitée, peu importe la profondeur. Pendant les opérations de mariculture visant le saumon de l’Atlantique, les échappées peuvent survenir à la suite de défaillances structurales au niveau des parcs en filet ou des composants d'amarrage, à la suite de défaillances d'exploitation ou de gestion survenues au cours des procédures habituelles de manipulation du poisson ou de gestion de l'élevage, en raison de vandalisme ou de défaillances biologiques (p. ex. attaques de prédateurs). La première ligne de défense à utiliser pour réduire les effets négatifs découlant des échappées doit comprendre l'ensemble des stratégies d’atténuation utilisables servant à empêcher que des poissons s'échappent de l'exploitation aquacole. Souvent, bon nombre des mesures d'atténuation ne peuvent être prises isolément dans le système de pisciculture fortement intégré. Il est donc difficile d'évaluer telle ou telle mesure en vue de calculer le rendement du capital investi pour atténuer les risques. Toutefois, certaines mesures d'atténuation peuvent être présentées de façon plus générale dans une courte liste des recommandations de haut niveau, dont voici quelques-unes :

- Les codes de confinement devraient devenir obligatoires dans les lois provinciales et devenir une condition du permis d'aquaculture ou une condition pour l'obtention de l'approbation d'exploitation. De plus, les ministères de réglementation devraient envisager d'élaborer une norme de l'industrie semblable à la norme norvégienne régissant les piscicultures marines, compte tenu de la preuve irréfutable que cette norme a permis de réduire de façon importante le nombre total de poissons s'échappant des piscicultures, et ce, pour l'ensemble du secteur aquacole du pays.
- Tous les sites d'aquaculture du saumon de l’Atlantique en eau douce et en milieu marin existants et potentiels devraient faire l'objet de nombreux relevés, qui permettraient de recueillir des renseignements pertinents pouvant aider à empêcher les échappées pendant les opérations.
- Pour la sélection de l'équipement approprié, on devrait faire appel à un ingénieur, pour s'assurer que tous les composants servant à la collecte de données sur certains sites ont été adéquatement conçus et sont de dimension appropriée avant de procéder à l'installation des piscicultures du saumon de l’Atlantique. L'équipement utilisé devrait être vérifié périodiquement pour évaluer sa conformité avec la conception technique, de manière à s'assurer qu'il continue de faire l'objet d'un entretien adéquat lorsqu'il est utilisé.
- Tout l'équipement utilisé et toutes les opérations exécutées devraient inclure les volets de la redondance, de la conception à sûreté intégrée et des marges de sécurité propres au milieu exploité, afin d'optimiser les chances que le stock de saumon de l’Atlantique fasse l'objet d'un confinement total tout au long du cycle de grossissement.
- Tous les exploitants devraient s'assurer que tous leurs employés reçoivent une formation adéquate et comprennent l'ensemble des procédures opérationnelles normalisées permettant d'utiliser l'équipement requis et de faciliter la manipulation du poisson et les opérations aquacoles de manière à réduire les risques que des poissons s'échappent.

- Enfin, dans l'ensemble, l'industrie du saumon de l’Atlantique demeure un secteur d'innovation qui doit conserver son attitude avant-gardiste à l'égard de la réduction des échappées ainsi qu'à l'égard des nouveautés du côté du matériel (p. ex., conception des parcs en filet, nouveaux matériaux de filet) et des procédures de manipulation.

INTRODUCTION

Escapes from aquaculture operations affect the fish farm operator through a loss of potential profits and negative public perception that can generally affect the marketability of farm-raised products. Fish farm escapes may also present additional indirect effects and liability issues for the operator. Escapes may come in close contact with both wild and stocked fish populations thereby serving as a possible connection for more aggressive horizontal transmission of disease and parasitic agents. Bridger *et al*. (2001) illustrated an extreme interaction between wild and stocked fish through escapes as the site crew actually recaptured a transmitter-implanted steelhead trout escape while changing a containment net during the study period. Escaped fish may also be attracted to aquaculture sites, increasing the number of fish aggregating near net pens. This, in turn, may further attract more opportunistic predatory species. With more free-swimming activity, the possibility for disease transmission or predatory attacks on the net pens increases and therefore may result in the further loss of contained fish. Finally, a public health risk exists if Atlantic salmon escape shortly after receiving a medicated feed or bath treatment. These escapes may be captured in recreational or commercial fisheries but will not have a sufficient withdrawal period to safely enter the human food supply (examples monitoring wild fish near aquaculture operations include Björklund *et al*. 1990; Ervik *et al*. 1994). This concern is diminished somewhat with the use of antibiotics dramatically reduced throughout the industry, although not eliminated, due to widespread use of vaccines. However, the industry still uses various pesticides to address sea lice infestation and most of these have a minimal required withdrawal period before consumption by humans is permitted.

The first line of defence to minimize any negative effects due to escapes must include all feasible mitigation strategies to prevent the occurrence of chronic and acute escapes from the farm operation. Escapes from aquaculture facilities may occur following structural failures of the farm infrastructure, operational/management failures during routine operations, and biological failures that include successful predator attacks and vandalism. Many Atlantic salmon escapes are preventable through appropriate attention to detail by farm management and staff and proper use of equipment that is appropriate for the site specific conditions of the aquaculture operation. Large-scale escapes, primarily caused by storm damage, may be preventable but require appropriate engineering design and dimensioning efforts, and deployment and maintenance of equipment capable of sustaining all anticipated storms experienced at the site. As such, this report will take a very narrow look at the farm escape issue to address physical containment of the cultured stock within the context of two primary questions:

- How might mitigation measures be used to prevent or reduce the likelihood of escape of European-origin fish from physical containment systems in Newfoundland and Labrador?
- How could these mitigation measures result in possible reductions in genetic, phenotypic, and/or ecological risks to wild populations?

This paper will provide a broad overview of freshwater and saltwater operations typically employed to raise Atlantic salmon on fish farms. An analysis follows of the very limited data available globally (sourced from Norway and Scotland) pertaining to the causes and scale of aquaculture escapes. An effort is made to determine the likelihood and severity of escapes by identifying the various causes and prioritizing mitigation options to prevent escapement. These areas will provide the greatest return on investment for the commercial operators and government regulators to prevent escapes. A detailed discussion is included to describe the causes for escapes as they relate to commercial aquaculture equipment and operations used presently in the Atlantic salmon farming industry. The list of mitigation options is compiled from global strategies already implemented in specific jurisdictions or other methods that are considered to provide a reasonable return on investment based on the discussion presented throughout this paper.

ESCAPEMENT OVERVIEW

DEFINING FARM ESCAPES

Escapement of farmed fish from hatchery and grow-out sites is still an issue for the aquaculture industry. In general, aquaculture operators have an economic interest to maximize the total number of stocked fish harvested from each facility per grow-out cycle. Losing fish as farm escapes is detrimental to this economic incentive, especially given the fact that escapes represent an increasing economic loss to the farm operation with each successive day the fish are held and fed on the farm. Farm escapes may also pose a risk to wild populations and ecosystems based on a number of contributing factors. The economic and environmental impact from farm escapes may be determined on the basis of: a) the likelihood (probability) for escapement; b) the magnitude (numbers) involved with each escape event; and c) the impact escaped fish may have on wild populations, the operation, etc. (Naylor *et al*. 2005). While there might be some debate regarding the total escape impact on the receiving ecosystem, there is little debate that the first line of defense to minimize any impact is to ensure every effort is made to consistently contain all of the cultured Atlantic salmon stock throughout the entire grow-out cycle. In this regard, the growth cycle includes all handling and operations from hatchery production through stocking of sea cages to harvest.

Based on the frequency and scale of the events, escapes from aquaculture operations can be classified as either chronic or acute loss of reared fish:

- **Chronic losses** are represented by the ongoing ‘leakage’ of stocked fish to the outside environment occurring anytime during the grow-out cycle. These losses are sometimes over an extended period, without any warning whatsoever to the site crew. Examples of chronic escapes of Atlantic salmon include losses through typical handling and site operations that are located outside of the confines of the containment netting.
- **Acute losses** may be dramatic in regards to the numbers of fish involved and may occur quite suddenly and sometimes without notice. The predominate events that may result in an acute loss of fish involve severe weather, devastating predator breach of the containment netting, general catastrophic failure of equipment, or unexpected vandalism of the netting to allow large scale losses of the contained fish.

EXTENT OF AQUACULTURE ESCAPES

Escapement of farm-raised Atlantic salmon occurs in all jurisdictions allowing commercial aquaculture operations to raise the species. Nearly every Atlantic salmon farming region has implemented legislation, regulations, and/or policies associated with the containment, reporting and monitoring of escapes from the aquaculture facility. Naylor *et al*. (2005) summarized regulations associated with aquaculture escapes by region up to 2003. However, acquiring a complete picture of the global incidence of Atlantic salmon escapes is difficult primarily due to the general lack of official data maintained to enumerate escapes resulting from each incident. Thorstad *et al*. (2008) provides a review of documented incidences of Atlantic salmon escapes from fish farming activities located in numerous jurisdictions globally.

Official Atlantic salmon escape statistics are also expected to underestimate the actual number of cultured fish that leave the containment volume despite a high level of global governmental oversight for two primary reasons. First, chronic leakage or events that may result in small numbers of escapes are generally unreported or not required in some jurisdictions if the expected number of fish having escaped is below a government specified threshold. Second, farm reports are more likely to optimistically underestimate the actual number of escaped fish following severe events that resulted in the loss of a large number of fish. Numerous inventory counting methods and technologies are used by the industry throughout the grow-out cycle in an attempt to determine stock numbers. However, in reality, the only accurate inventory numbers of fish raised within each cage, site and region is acquired after the Atlantic salmon have been harvested and enumerated while being packed for sale. The degree of underestimation of farm escapes is considered quite high by some observers with Sægrov and Urdal (2006) expecting that only 12-29% of the actual number of escapes is reported. This estimation may also be somewhat speculative, but illustrates the wide disparity in confidence associated with industry reporting of escapes that is provided to government regulators.

Norway maintains a comprehensive national database on reported numbers of escapes from their Atlantic salmon aquaculture industry, which is readily available from the Statistics webpage on the Directorate of Fisheries' website. The Norwegian Atlantic salmon farming industry has generally increased its annual production since 1998 to more than 3.25 billion Atlantic salmon raised during the period of 1998-2011. During this same period, more than 450 million fish, representing nearly 14% of the total Norwegian Atlantic salmon aquaculture population, were lost in the grow-out cycle as mortalities, escapes or other unclassified losses. Reported Atlantic salmon escapes represented just 0.17% of the total Atlantic salmon population stocked or 1.25% of the total losses reported throughout the grow-out cycle in the same period of 1998-2011. The annual loss as reported escapes peaked at 0.38% of the total annual production in 1998 and 2006, with more than 920,000 Atlantic salmon escapes in 2006 according to the official government statistics on the subject. This level of escapes declined dramatically in 2007 to 0.11% of total production (290,000 fish) and has remained below 0.10% of production since then despite year-over-year increases in annual production during the same period. While these percentages are quite low, the financial and potential for environmental impact from escaped Atlantic salmon cannot be overstated given the fact that these percentages actually represent more than 5.6 million individual Atlantic salmon that have been reported as escaped from Norwegian fish farms spanning the period of 1998-2011. Furthermore, this number of escaped Atlantic salmon is close to the estimated number of wild Atlantic salmon returning to Norwegian rivers to spawn in some years.

Norway has required mandatory reporting of escapes since the 1980s. Two significant events occurred in the mid-2000s that were likely major contributing factors resulting in this dramatic decline in the number of reported escapes from fish farms:

1. Norway implemented its technical standard NS 9415 through legislation on 1 April 2004. A further revision, to strengthen the standard, occurred in 2009. This standard was implemented to "… reduce the risk of escape as a result of technical failure and wrong use of marine fish farms" and "… sets requirements as to how marine fish farms shall be operated in order to be acceptably escape-proof." The standard requires that all sites must be classified with regards to environmental/oceanographic conditions (e.g., wind, waves and current) and major fish farm components must be independently certified for the specific site conditions prior to installation. Accreditation is central for the success of the Norwegian standard involving an accreditation body that oversees the standard and participating companies, accreditation of companies that certifies specific equipment and producers according to the standard and accreditation of surveying and inspection companies. These accredited components ensure that manufacturers certify their products, producers use certified equipment, mooring systems are designed by accredited companies for the site specific conditions, and installation of the entire system is controlled and verified by independent certified companies based on the engineered plans.
2. In the same timeframe, forensic DNA methods were evaluated in Norway to identify specific farms and cages of origin of Atlantic salmon escapes (Glover *et al*. 2008). The "DNA stand-by method" has since been successfully used in seven cases to assist government officials in identifying potential sources of escaped fish, including Atlantic salmon, rainbow trout and Atlantic cod, while not requiring cost prohibitive tagging all cultured fish by industry (Glover 2010). Less than 50 escapes were analyzed in each of the cases and all involved companies have accepted any resulting fines for not reporting the escape events. None of the cases have been challenged by the

companies in court (Table 1). Similar DNA methods have been used to identify escaped Atlantic salmon captured in the wild in Scotland and Maine with a high level of success (in the case of Maine, stock genetic verification must also occur prior to smolt entry to the marine site). This broad use of forensic DNA procedures in several jurisdictions clearly illustrates the established methods used to accurately determine the source of Atlantic salmon. These same methods should be quite easily implemented within the Canadian Atlantic salmon farming sector, including in Newfoundland.

Table 1. Summary of six cases using the Norwegian DNA stand-by method (taken from Glover (2010)). Escapes Assigned (%) refers to the percentage of escapes analyzed directly assigned to the three most likely farm samples.

Case	Species	# Escapes Analyzed	Farms/Cages Sampled	Escapes Assigned (%)	Comments
1	Atlantic salmon	29	7/16	72, 7, 7	Single cage and farm identified. Company subsequently admitted to losing fish. Fined by authorities.
2	Atlantic salmon	44	7/8	25, 22, 20	No clear result. Multiple cages, farms and companies implicated. Case complicated by presence of fish from multiple sources. No legal case initiated.
3	Atlantic salmon	48	7/9	98, 2, 0	Single cage and farm identified. Rapid sampling of escapees and differentiated baseline samples gave distinct result. Company fined and forced to compensate for analytical costs.
4	Rainbow trout	35	6/7	91, 6, 3	Farm(s) operated by single company clearly implicated. Only producer in region. No legal case initiated due to circumstances unrelated to the method.
5	Atlantic salmon	47	5/7	89, 6, 2	Single cage and farm identified. Legal case in development at time of publication.
6	Atlantic salmon	40	1/1	0	Escapees excluded from a farm reported to have lost fish. This led to sampling all farms in region to identify the “unreported” source. Case under analysis at time of publication.

Introduction of the Norwegian technical standard (NS 9415) for marine aquaculture sites is often considered to be the major contributing factor in reducing the number of escapes and escape events in Norway given the timing for its implementation and annual decline in reported escapes. There is little dispute that requiring deployment of proven equipment, which is also certified to be capable of withstanding site specific conditions, will be beneficial. Perhaps equally important would be the government’s new capability to increase accountability using DNA methods to identify the source of Atlantic salmon escapes that have resulted in uncontested fines to the companies involved. While it is not illegal to have a breach in the farm containment in Norway, failing to report a possible escape event, which is illegal, should be greatly minimized following the presence of the DNA stand-by method that can later identify a negligent farm operator. The DNA stand-by method, coupled with the

Norwegian standard for marine farm operations, will incentivize farm operators and managers to maintain a higher level of diligence over their operations and equipment. These appear to have worked to set the Norwegian fish farming industry on the right path towards sustainability in regards to aquaculture escapes.

Maine does not have a prescriptive umbrella standard regarding the site installation as part of its regulation. However, Maine has implemented many of the same aspects within regulation to protect wild Atlantic salmon populations that have been placed on the Endangered Species List. Within this system, the farm operator must submit an acceptable marine containment management system that must include a list of site specific critical control points where escapes may potentially occur and appropriate corrective actions. Likewise, a site audit with respect to the submitted containment management system is required both annually and following a reported escape event. Not all escapes are reported but rather only those likely to have occurred involving more than 50 fish larger than 2 kg within a 24-hour period or escapes involving the loss of more than 25% of the net pen biomass if the fish involved are smaller than the 2 kg benchmark weight[1]. As noted previously, DNA analysis is used in Maine to ensure that the stocked fish are from North American origin and to mark stocked individuals so that assignment may be possible to identify unreported escapes to a specific site for prosecution purposes. This approach, taken as a whole, has reportedly helped to mitigate Atlantic salmon escapes in Maine with the objective of allowing fish farming while protecting wild Atlantic salmon stocks.

Marine Atlantic salmon farming in Newfoundland and Labrador is localized to the south coast of Newfoundland where year-round biological conditions for the rearing of Atlantic salmon fish are met. The industry has experienced a significant increase in production in recent years, with 78 sites licensed for Atlantic salmon and steelhead trout farming in 2010 and total production at 12,881 tonnes. The industry must comply with a mandatory Code of Containment[2] as a condition to operate in Newfoundland and Labrador, with aspects of the Code audited by the provincial government throughout the year. The total number of reported escapes has decreased over time with no reported Atlantic salmon and 32,443 steelhead trout escapes reported in 2010. However, the industry also struggles with accurate inventory reconciliation, like all other farming jurisdictions, and cage/site population shrinkages may also include unreported small-scale chronic losses of stock by escape. Escapes are certainly possible in Newfoundland and Labrador with at least 20,000 Atlantic salmon reportedly escaping from a single cage during a single non-storm event in September 2013.

ATLANTIC SALMON AQUACULTURE AND OCEANOGRAPHIC CONCEPTS

FRESHWATER CONTAINMENT – LAND-BASED OPERATIONS

The grow-out cycle for Atlantic salmon begins within land-based hatchery production facilities. Here eggs and milt are stripped from mature broodstock and mixed to fertilize and create “green” eggs. This process typically occurs every fall, although many companies are able to fertilize eggs most of the year through photo-/thermal-manipulation and the use of hormone implantation of broodstock. Within the normal development cycle, green eggs become eyed eggs by March of each year and eventually hatch as alevins or yolk-sac fry. Alevins absorb nutrients from their yolk-sac while hatchery staff entice these fry to consume tiny crumble feed. As they grow, fry are graded and split into an increasing number of larger tanks located at the hatchery facility to manage stocking density, fish health, food conversion ratio and growth. Atlantic salmon parr eventually undergo the biological process of smoltification when conditions allow and an acceptable size is reached (i.e., typically a minimum size of 50 g). The resulting

[1] Maine General Permit: Net Pen Aquaculture

[2] Code of Containment for the Culture of Salmonids in Newfoundland and Labrador, 1999

smolt are then transferred to sea cages to continue grow-out to the final target market size. Transfer of smolt from the hatchery typically occurs in the first fall following hatching (S0 smolt), in the following spring (S1 smolt) or during the next fall (S1.5 smolt).

In very general and basic terms, hatchery facilities typically take water from either groundwater (e.g., a well) or surface water (e.g., stream/river). Out of necessity, hatcheries using a surface water supply are located very close to the banks of the source stream/river. Well-fed hatcheries have no particular reason to be located near local surface waters that are likely to host endemic populations of fish. Water within the hatchery may flow through the entire system and exit following a single use (i.e., flow-thru) or varying quantities of used water may be properly filtered and recycled for continued use within the system (i.e., reuse or recirculating aquaculture systems) to increase control over water quality, particularly in locations having limited water quantity. Water that exits the hatchery facility is almost always stripped of dissolved and particulate organic material to reduce the environmental impact on receiving ecosystems from the facility. Solids removal may occur through use of a combination of mechanical filtration (e.g., drum filters), short but effective settle decks, and larger settling ponds that increase the residence time for departing water to increase the opportunity for particles to settle out. In all cases, collected particulate matter must be physically removed from the filter or settle area and disposed of in a proper manner as allowed by local authorities.

SALTWATER CONTAINMENT – NET PENS AND MOORING SYSTEMS

In most cases, smolts are moved from hatchery facilities to a wharf near the marine grow-out site in live haul trucks. From there, the transported smolt are usually transferred by hose from the trucks to an awaiting well boat or barge that is equipped with the appropriate tank capacity to complete the transport to the site. In some cases, the live haul truck is driven directly onto the barge to complete smolt transfer to the marine site thereby eliminating one handling procedure and at the same time decreasing the opportunity for system failure and escapement.

Atlantic salmon are raised in net pens through the marine phase of the grow-out cycle. Maintaining complete integrity of each net pen is essential to ensuring full containment of the Atlantic salmon stock. Loverich and Gace (1998) classified the predominant net pen used in the global Atlantic salmon aquaculture industry as "gravity cages." Gravity cages hang a net within the water column and rely on the force of "gravity" to maintain its shape and volume. This design is presently used in most of the commercial grow-out operations globally, especially for those operations that raise Atlantic salmon, due to their simplicity in design, ease of operations, and lower cost per cubic meter of growing volume compared to other cage designs (Figure 1).

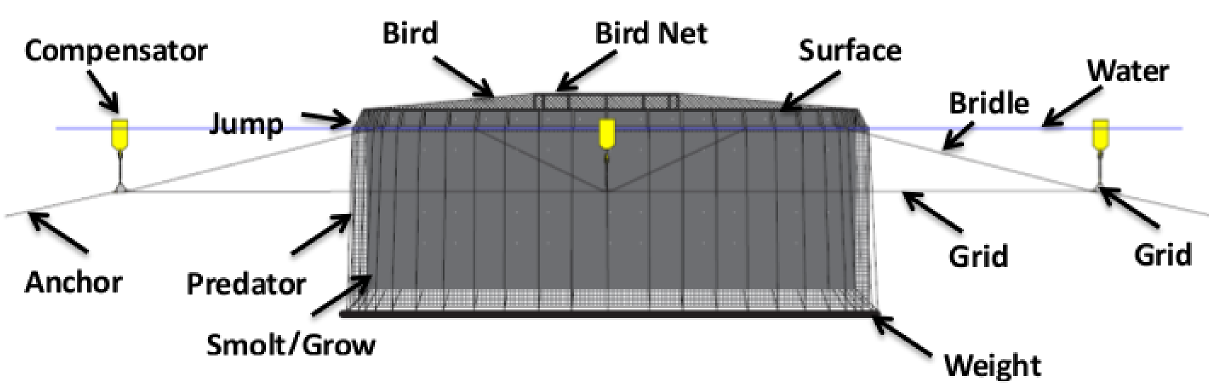

Figure 1. Typical gravity net pen arrangement used predominately throughout the global Atlantic salmon farming industry (drawn by P. Dobson).

Gravity cages have a structural floating **surface collar** that is primarily manufactured using a high-density polyethylene (HDPE) pipe in the modern Atlantic salmon farming industry although wooden and steel surface collars may still be used in some jurisdictions, albeit at a greatly diminished level. In the majority of deployments, the HDPE collar is comprised of two separate pipe rings that are connected using a series of stiff uprights or stanchions such that the inner concentric ring is shorter than the outer concentric ring. Some operators have opted to use a three-ringed collar to provide a wider work platform while a single collar ring can also be used particularly in locations that are plagued by marine mammal predators that use the multi-ring configurations as a place to rest. The total buoyancy of all surface collar rings must provide sufficient flotation to maintain the entire system (including a series of nets with expected biofouling and weight ring) at the surface while withstanding the downward forces from the mooring system, which also increases with increasing drag (from biofouling and current velocity) due to the angle of the bridle line. The surface collar rings are also typically filled with Styrofoam plugs that provide redundant buoyancy in cases where the integrity of the surface pipes is jeopardized (from structural fatigue and damage, poor workmanship, or vandalism) allowing water to enter and potentially sinking the net pen below the water surface.

Each net pen may have a series of nets that are affixed to the surface collar and hang within the water column to either contain the growing fish stock or keep predators out. The primary containment net is comprised of a twine mesh that is typically sized (usually as a **smolt or grower net**) based on government requirement, stock insurance policy or fish farm experience to prevent fish escape. The containment net is tied to the internal collar float pipe and has an upper portion (typically about 1 m high) that extends from the water surface to the collar handrail – the **jump net**. The purpose of the jump net is to prevent the escape of farmed fish as they frequently jump out of the water while the containment net below the water surface prevents the loss of Atlantic salmon as the stock schools in a circular pattern within the confines of each net pen. Various materials have been used for the containment net depending on the objectives of the fish farm operators. The industry initially began by using knotted net mesh. However, this practice was eventually replaced by the use of knotless netting material, primarily of nylon or polyamide, to decrease total material required to manufacture a net and therefore decrease the total net weight and associated costs. Presence of knots in mesh also decreases the twine strength where the knots are located but the use of knotless material also addressed this shortcoming. Another trend within the industry is towards net materials that have greater breaking strength. However, in many cases the fish farm operator is targeting the same industry accepted net breaking strength but stronger material allows the use of smaller twine diameter on significantly larger net pens to control total net weight as net pen size increases. The overall result of this practice is that actual net strength is not necessarily increased from use of stronger twine material and therefore benefits are not necessarily accrued from an escape prevention perspective.

Two other nets are typically deployed within a complete net pen system, although these nets have little to do with escape prevention per se but rather are used to keep predators away from the target fish stock – bird nets and predator nets.

- **Bird nets** are generally light weight and spread across the entire open surface area of individual net pens to serve as a deterrent to predatory or scavenging bird species that can act as a nuisance to the farm operators and the fish stock. With larger collar net pens (>70 m circumference), bird nets must be held up from the water surface by using a **bird net stand** that is positioned in the middle of the collar circumference. Fish escapement through bird nets is considered to have a very low rate of occurrence even though bird net mesh tends to be a larger size than the containment net as its primary purpose is to impede entry of the local predatory and scavenging birds. Bird nets tend to be deployed as a permanent part of the net pen system. However, farm operators sometime remove the bird nets when the contained Atlantic salmon have reached the target harvest size as the fish are now too large to be effectively carried away by most nuisance bird species. Ironically, it is at this same size that the large Atlantic salmon would be strong enough to jump out of the net pen and escape unimpeded if the bird net has been removed during the harvesting process.

- **Predator nets** are deployed in specific jurisdictions as necessary to protect the fish stock from predatory attacks by aggressive large fish, marine mammals or sharks. These predators can inflict severe damage to the fish farm net infrastructure and stock of fish in a short period of time. Aquatic predators can also provide ample opportunity for escapement to occur through the predator entry hole long after the predator has left the net pen area. Predator nets are affixed to the outer float ring of the surface collar and extend down within the water column beyond the depth of the primary net and frequently run along the bottom of the containment net such that the predator net is totally encircling the primary net. A shark guard net may also be required outside of the bottom of the containment net if shark attacks are prevalent in the area. Use of and seasonal requirements for predator nets are typically dictated by government authorities or stock insurance policies based on the presence of local predator populations. Predator nets usually serve absolutely no purpose to the containment of the Atlantic salmon stock and therefore are manufactured with net mesh that can be several times larger than the biggest containment net mesh (i.e., predator nets frequently use 4-8" net mesh).

The cylindrical shape of the containment net must be maintained to provide the total water volume required for the Atlantic salmon biomass stocked in each net pen. However, the entire volume is only afforded to the fish stock in locations having no (or very low) current or nearing the high or low water marks of the tidal cycle when the current goes to zero prior to reversing. Otherwise in current the flexible net hanging from the surface collar will follow the water current resulting in bagging of the net and loss of grow-out volume. Loss of volume can be dramatic in high current conditions and will increase fish stress, fish mortality and product downgrades through exterior abrasion of the fish on the bagging containment net and overstocked populations. The Atlantic salmon farming industry may minimize product downgrades by reducing fish stocking density to an acceptable level when the net is bagging and use of knotless netting to minimize abrasive damage that might occur when fish rub against the bagging net. Structural measures have also been taken to minimize the degree of net bagging in current. In low current, net bagging may be mitigated by tying small individual weights to soft eyes integrated in the containment net at the intersection between the side and bottom net panels to hold the volume through gravity. Individual clump weights are inadequate on sites having high current velocity. Here, gravity cages have been fitted with a continuous **weight ring** (or sinker tube) in the same general location to maintain the net shape and volume. Weight rings tend to be small diameter HDPE pipe filled with sand, concrete or steel wire cable/chain to provide the in-water mass considered necessary to counter the effect of the site current on net bagging and volume deformation.

Net pens are held spatially in a leased area of ocean space using an appropriate mooring design. Turner (2000b) provided the anecdote that "... a fragile glass light bulb thrown into violent storm waves, will survive, because it is not restrained." For this reason, mooring designs must strike a careful balance between system restraint spatially (i.e., mooring stiffness) and an appropriate degree of movement to allow for storm surges and tidal ranges (i.e., mooring elasticity) based on the site specific oceanographic conditions. Net pens as described have been moored individually or within a group, frequently referred to as a flotilla. Mooring net pens individually is achieved by using 3-4 mooring lines that connect the surface collar to the seabed. However, the most common mooring strategy is to use a submerged grid system, with anchor lines arranged in a catenary shape to secure a group of net pens on a site lease (Figure 2). The components of the anchor line (i.e., chain, rope, buoy) may be specified in an effort to optimize the stiffness/elasticity characteristics required for the site conditions. For instance, in Norway relatively very little of the anchor line is chain so that most of the flexibility in the mooring is provided by the elasticity in the rope material used rather than the geometric flexibility of the catenary shape. The submerged mooring grid system is located at any depth in the water column as determined by the vessel traffic that must visit the site and the oceanographic conditions present. Sites located in higher energy typically deploy the submerged mooring grid at a greater depth to dampen the loads experienced. Specifics of submerged grid systems from the surface collar to the seabed include:

- **Bridles** – Bridles secure the net pen collar to the submerged grid system. Each bridle extends from a submerged **grid plate** up to the surface collar where the bridle is tied to hold the net pen spatially. At least two bridle lines extend from each grid plate to the surface collar so that the environmental load transferring to the surface collar is diminished at each point source where the bridles are tied. This strategy distributes the total load experienced from environmental forces (i.e., wind, wave, current, tide). Use of additional bridles in higher energy conditions would help to further distribute the total loads experienced at each point source of attachment to the surface collar.
- **Compensator buoy** – A length of chain or rope also extends from the top of the submerged grid plate to a surface compensator buoy located directly above the grid plate at the water surface. The primary purpose of this intermediate buoy is to support the weight of the mooring grid and the compensator buoy must be appropriately sized to do so. Other purposes might include site marking in some jurisdictions.
- **Grid cell** – Four grid plates/compensator buoys mark the four corners of a mooring grid cell. Submerged **grid lines** connect adjacent grid plates to form the perimeter of each grid cell. Grid lines must be sized to absorb the loads transferred along the submerged grid mooring system and deployed at a depth that must not interfere with site vessel traffic that frequently enters the site to address various tasks required to operate the site successfully.
- **Tension member** – Each submerged grid plate is connected through the water column downwards to the seabed along at least one **anchor line**. However, multiple anchor lines from specific grid plates can be expected on the grid corners and on grid sides that experience high energy. Typically synthetic rope is used to extend the anchor lines through the water column but its use terminates prior to reaching the seabed to prevent chafing and subsequent failure of the mooring system. At this depth, heavy chain is shackled to the anchor line rope and continues along the seabed for a length typically of at least 15-30 m before reaching the anchor line terminus. Catenary arrangements in marine applications work best with heavy anchor lines as the resulting slack line catenary curve provides a low angle of pull on the anchor (i.e., the heavy chain is on the seabed) thereby increasing the force required before the anchor drags and fails.
- **Anchor** – Several basic anchor types, including clump weights, embedment anchors and helical screws or rock bolts, are available for mooring cage systems to the seabed. Each of these anchor types have specific uses dependent mostly on seabed characteristics and anticipated environmental loads. Clump weights are best used on coarse rocky substrates with low load conditions, embedment anchors require penetration within silt, sand or mud substrates and sufficient for high loads, and screws require a solid foundation of bedrock and again fine in high loads. Clump weights are the least reliable anchor type and require a significant amount of mass to provide a comparable holding capacity when compared with embedment anchors in a similar substrate. For instance, clump weights comprised of concrete or steel retain about 60% or 80% of their dry weight after submersion in water, respectively. Therefore, a reasonably sized, highly efficient embedment anchor providing 30 tonnes of holding power can be replaced by a single 50 tonne concrete block for the same deadweight holding capacity. The final holding capacity of this clump weight also will be affected by the clump weight design, ability of the clump to sink within the substrate to increase holding capacity, and the coefficient of friction between the substrate and clump weight to prevent or allow slippage under tension. Generally the holding power of an embedment anchor is dependent on the anchor surface area perpendicular to the direction of tension, penetration depth into the seabed, specific gravity of the sediment, and cohesive properties of the sediment (a function of grain size, grain shape, and soil chemistry; Kery 1996). Proper mooring of a submerged grid system might require deployment of a multitude of anchor types and

sizes based on the consistency of substrate on the site and environmental loads anticipated from each direction to maximize holding strength at a site. Additional important considerations are that generally drag embedment anchors are not useful with bottoms having an uneven contour where helical screws/rock bolts or clump weights are better equipped and low scopes resulting from steep gradients are not appropriate for drag embedment or deadweight anchor use (Turner 2000a).

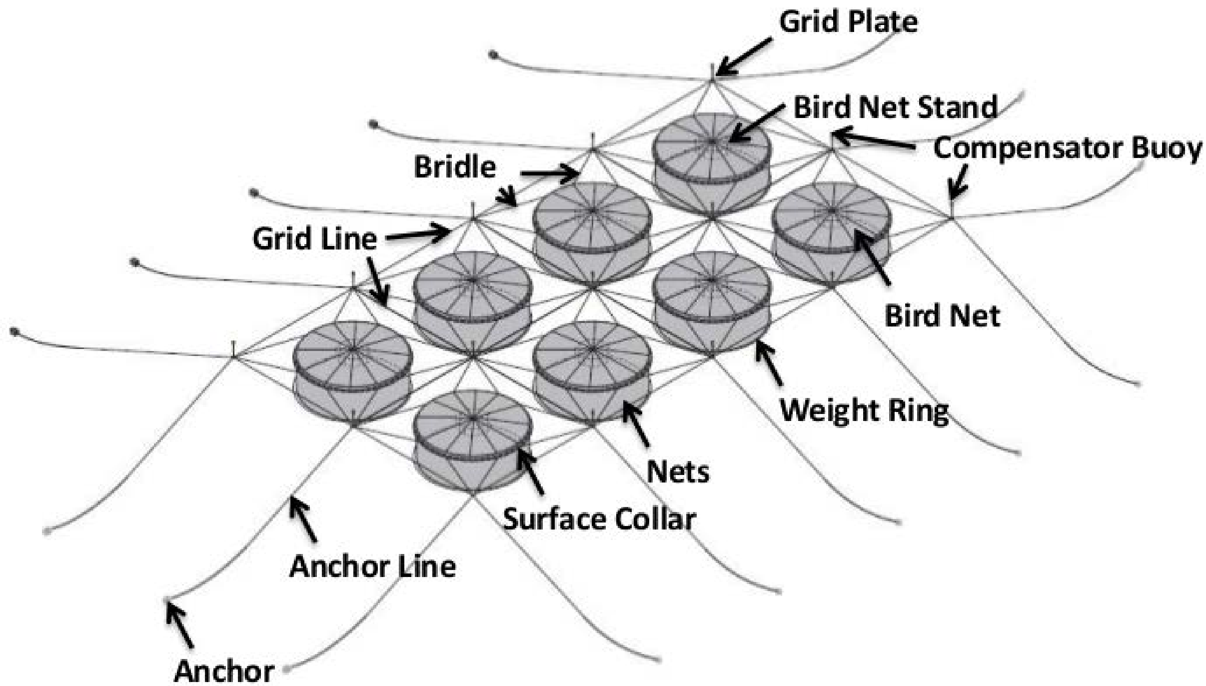

Figure 2. Line drawing of a group of net pens held together spatially using a submerged mooring grid (drawn by P. Dobson).

Direct handling of the Atlantic salmon stock is generally kept to a minimum throughout the marine grow-out cycle to reduce stress on the fish and resultant risks associated with poor fish health, particularly in areas with warmer water temperature. The exception to this strategy is the multiple transfers of sea lice infested Atlantic salmon to well boats to allow soaking in pesticide bath solutions and their return to net pens following treatment. Smolt are frequently single stocked in each net pen such that the harvest number and size of individuals provide a target harvest density for the size of the net pen being stocked. For example, a 100 m circumference net pen (32 m diameter) having a net depth of 10 m in the water (i.e., excluding jump net) has a total calculated volume of 8042 m^3. Assuming a target harvest density of 20 kg/m^3 and 4.5 kg target harvest size this net pen can be single stocked with 160,840 kg of Atlantic salmon or 35,742 individuals. Some companies might overstock each net pen to account for the anticipated initial saltwater entry mortality and a generally accepted monthly mortality that occurs in all livestock production. Using this approach, each net pen might be overstocked by 5% or stocked with about 37,500 smolt to each net pen as the company "self-insures" for these anticipated losses from the outset while expecting to meet the same final stocking density of 20 kg/m^3. Overstocking will also ensure the entire target population is indeed raised in each net pen given the difficulty throughout the industry to consistently and accurately count the total number of fish involved. In a few cases, fish farm operators might choose to initially double or triple stock each net pen and later plan to grade and split the stock into additional net pens as the Atlantic salmon grow and exceed present net pen stocking density capacity. However, multiple stocking is generally not a desirable strategy given the need to split the stock at a specific time or risk overall fish welfare, the inherent difficulty to equally split the stock and track numbers that are entered to each subsequent net pen, and high risk of escapement during the stock splitting procedure especially if using an underwater swim-thru approach.

During the 15-24 month marine grow-out period, Atlantic salmon fish farms are typically visited every day – with the exception of foul weather days – primarily to feed the fish stock. Daily site visits also allow the crew to generally observe the well-being of the fish, check for the presence of predators around the outside and inside of each net pen, and generally monitor the integrity of the mooring grid system by observing the proper alignment of surface compensator buoys to indicate whether an anchor(s) is dragging, and inspect collar bridle connections. Divers are generally included in the site routine at least one day each week to remove dead fish and visually inspect the integrity of the net panels for holes. Although technology can now replace divers to collect dead fish using air lift-up systems, the use of divers to visually inspect nets underwater remains an integral part of the site routine, especially given that good divers are sometimes the first to become aware that a portion of the stock might be missing, as seen visually from the relative size of the population, and can then determine the cause of this otherwise unreported escape event. Thorough underwater inspections are also generally required at least twice each year (i.e., in the fall to prepare for the winter storm season and in the spring as the worst storms subside) and quickly following every major storm event to observe and report on overall structural integrity of the nets and mooring system. Dive reports are usually required by the fish farm operator and include sufficient information that a proper forensic diagnosis might be completed as necessary following an escape event.

The stock is fed multiple times each day using either feed boats that tie to individual net pens to complete the meal feeding or from a centralized feed system that manually or automatically provides calculated feed amounts to each net pen population through feed pipes that extend between the moored feeder and individual net pens. The allotted feed can be calculated from feed tables based on the biomass present, water temperature and assumed food conversion ratio. Alternatively, cameras can be used to try to monitor the feeding behaviour of the Atlantic salmon stock through detection of excess feed pellets. Successful use of cameras for this purpose can be limited in locations that have high tidal current that easily washes feed pellets away from the net pen volume, where high organic loads are present in the water column reducing underwater visibility, and in large volume net pens where the camera field of view is too small to be effective. With proper use, both feeding strategies can be used to monitor for excess feeding. In some cases a dramatic change in the feed requirement of the assumed fish population can indicate a fish health concern or loss of stock, presumably from escapement, predator consumption or theft.

The fish farmer must contend with biofouling of the nets during the grow-out cycle. Net biofouling is addressed either through scheduled net changes as necessary or more frequent net cleaning while deployed in the water. Net changing requires the farm operators to carefully untie the present fouled net, placement of the new clean net outside of the fouled net, removal of the fouled net and securing the new clean net to the collar and any weighting system at depth. Net changing is a common practice within the fish farming industry, although it does present an additional handling of fish farm infrastructure that can result in a loss of fish. The Atlantic salmon eventually grow to reach the target harvest weight. The stock is harvested, bled and returned to shore for final processing prior to being sold to the marketplace.

REVIEW OF BASIC OCEANOGRAPHY CONCEPTS

Marine aquaculture sites exist in a wide variety of oceanographic conditions. The vast majority of Atlantic salmon farm operations are located in coastal protected locations that have relatively low energy compared to the open ocean environment. However, the industry trend is moving towards more exposed locations where use conflicts for ocean space is less but the level of energy experienced in these locations is dramatically higher. The accessibility to the farm infrastructure is also diminished in more exposed open ocean environments. Often daily farm visits are not possible due to frequent inclement weather conditions (e.g., wind, waves, ice) that may become unsafe for consistent human presence. The capital and operational investment required to establish and farm in higher energy conditions[3] will also be greater as the net pen and mooring systems must be considerably more robust to prevent component fatigue leading to progressive net pen and mooring failure. All of these issues must be considered with regards to the possibility for fish escape as farm infrastructure is designed and deployed (Table 2).

The vast majority of fish farm infrastructure is located below the water surface where the nets and mooring system are deployed. Water will move through these components as a result of wind induced current, tidal currents, ocean currents and freshwater runoff. The specific combination of these currents and their general effect on the structural integrity of the fish farm will depend largely on the location of the aquaculture site. Surface ocean currents occur primarily due to the drag created by prevailing winds although specific current patterns may also be influenced by water salinity and temperature gradients, bottom topography, presence of land masses, and rotation of the earth. Surface ocean currents generally follow prevailing wind patterns with cooler waters moving from each pole and circulating towards the equator to be warmed before flowing back towards the respective pole. This circulation is affected by the Coriolis Effect such that ocean current direction is clockwise in the northern hemisphere but moves counterclockwise in the southern hemisphere similar to the global prevailing wind patterns. The surface current speed also diminishes with depth. Each successive layer of water that becomes part of the surface current will be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere compared with the layer of water above. This phenomenon – Ekman Transport – will result in a greatly diminished current speed at the bottom of the current (about 4% of the surface current) that is also flowing in the opposite direction compared with the surface current due to the resulting spiral established with depth. Surface ocean currents are reasonably consistent and should be considered a permanent feature when planning aquaculture site development (Figure 3).

As noted, aquaculture operations located in more exposed open ocean environments experience larger waves and therefore greater wave energy. Surface waves are formed as wind blows over a body of water. As wind blows, the water surface condition, or sea-state, progressively moves from smooth to ripple and chop waves until the wave condition is fully developed. The wind speed, wind duration, distance travelled over open water (or fetch), water depth and original sea-state all affect the resulting wave height, wave length and wave period during a wind event. A sea-state is fully developed when the wind energy equals the energy lost by breaking waves (given that the required wind duration and fetch is also present) and therefore the wind generated waves cannot grow any further. Swell represents a wave that has a greater wavelength and wave period as a result of a distant storm. Figure 4 illustrates the primary characteristics of regular sine waves that are not influenced by additional factors that might complicate the basic wave structure including:

- wavelength (L) is the distance between two identical points on a wave (e.g., distance from crest A to crest B);
- wave height (h) is the distance within a wave between the crest and trough measured within the same wave cycle;
- wave amplitude (h/2) is the height of the wave above the calm water line and is typically equal to half of the wave height;
- wave period (P) is the time required to complete one wavelength (e.g., time required for crest at point A to reach point B); and
- wave velocity (V) is the calculated speed of the moving wave and equals L/P.

[3] A marine or freshwater environment which is characterized by a high energy level and turbulent motion as created by energetic waves, currents, and/or winds.

Table 2. Key distinctions between coastal and exposed/offshore aquaculture site characteristics and operations (adapted from Muir and Basurco 2000).

Characteristic	Coastal	Exposed/Offshore
Location/Hydrography	- 0.5-3 km from shore - 10-50 m depth - Within sight of land - Usually at least semi-sheltered - Seasonal ice conditions may occur	- 2+ km from shore - Generally within continental shelf zone - Possibly open ocean with no shelter
Environment	- Significant wave height ≤ 3-4 m, usually ≤ 1 m - Short period winds - Localized coastal currents, possibly strong tidal streams	- Significant wave height ≥ 5 m, regularly 2-3 m - Oceanic swells - Variable wind periods - Possibly less localized current effects
Access	- ≥ 95% accessible on at least once daily basis, landing usually possible	- Usually > 80% accessible, landing may be possible but periodic (e.g., every 3-10 days anticipated)
Operation	- Regular, manual involvement	- Remote operations, automation and mechanization required

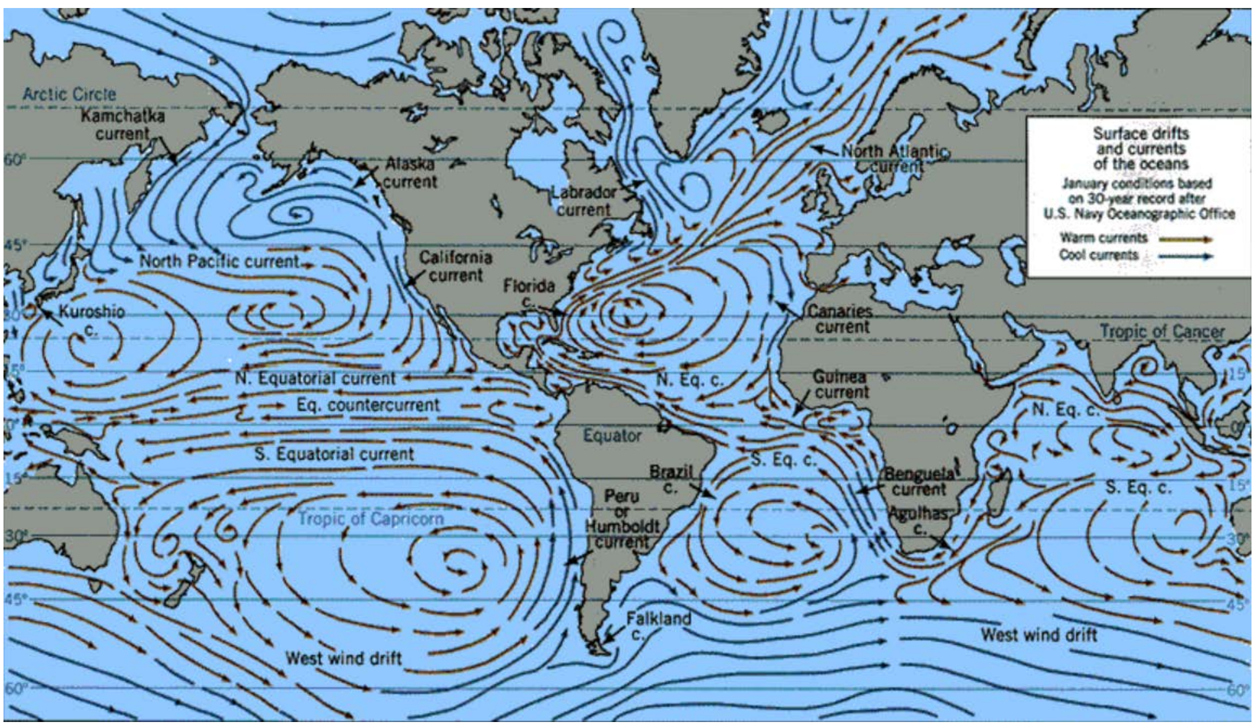

Figure 3. Prevailing global ocean currents (Annenberg Learner).

The sea state can be characterized based on the maximum wave height during a specific wind event. A more frequently used statistic is the significant wave height, which is calculated as the average height of the highest one-third of the waves.

Water within a wave actually does not move forward with the passing energy. However, the orbital motion within a wave results in water particles moving forward with the crest but moving back to its original position with the trough. The orbital velocity within a wave decreases with depth until the wave energy is completely dissipated at the wave base, which is located at a calculated depth of about half of the wavelength, especially in deep water conditions. Wave energy will therefore have a direct impact on all fish farm infrastructure located directly on the surface (e.g., surface collar and compensator buoy) but also the portions of the nets and submerged grid system including the bridles that are present above the wave base.

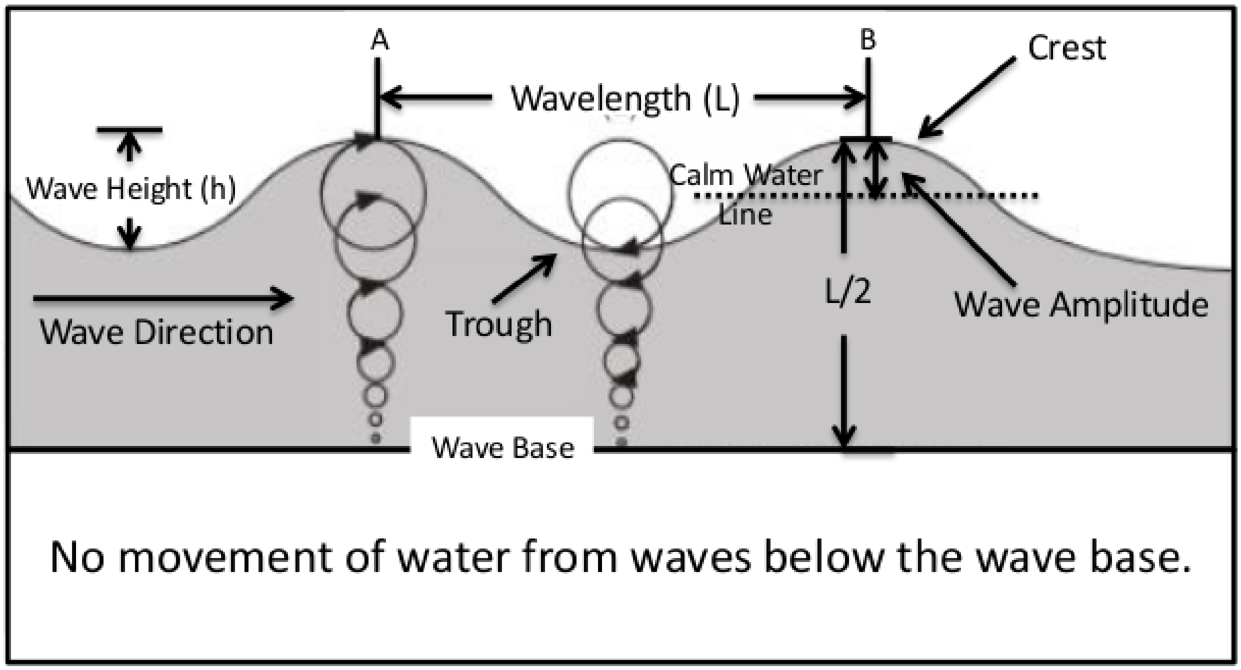

Figure 4. Overview of regular sine wave characteristics, especially in deep water conditions.

Tides have wave characteristics with a very long period that may be 12.4-24.8 hours and a wavelength that may be up to thousands of kilometers. The crest of the tide is observed when high tide reaches the shore while the trough is represented by low tide. The tidal range (wave height) may vary by region between microtidal (e.g., Gulf of Mexico) and macrotidal (e.g., Bay of Fundy). Because tides are essentially waves that have exceptionally long wavelengths, their orbital motion extends to depths that are calculated to be deeper than the average ocean depth. Therefore tidal energy impacts all of the water within the oceans and indeed all fish farm infrastructure. Tides may crest on shore once each day (diurnal), twice each day (semidiurnal) or represented by a mixed tide where successive high tides are dramatically uneven. Tides are not caused by local wind activity like surface waves but rather the gravitational impact of the sun and moon on the earth. As a result, tides are very predictable with regards to occurrence and height (Figure 5). The moon produces the greatest effect on the tide given its closer proximity to earth than the sun. These gravitational differences result in larger tidal range (spring tides) twice each month when the sun and moon are aligned in relation to the earth (i.e., new and full moon phases) while the moon and sun effects compete during the first and third quarter moon phases to cause a lower tidal range at those times monthly (neap tides). Each rising (flood) and falling (ebb) tide will transfer a significant amount of energy to fish farm infrastructure located throughout the water column in a relatively short period of time each and every day. This must be considered when designing specific farm components. Daily farm operations must also be planned to minimize the tidal effects on the fish stock and site staff while eliminating the possibility for escape.

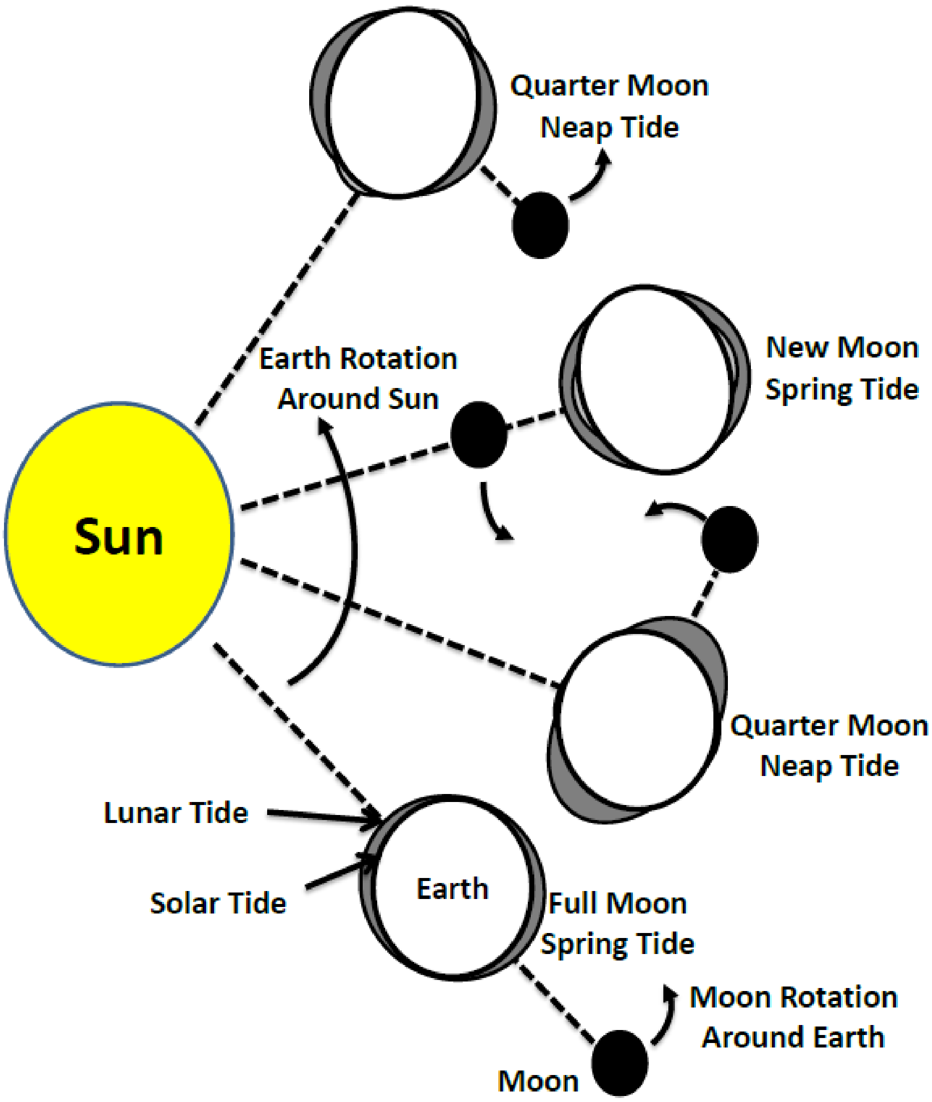

Figure 5. Tidal range changes within each month based on the position of the moon relative to the earth and sun to provide two higher (spring) and two lower (neap) tides each month when the moon and sun are aligned or not, respectively.

The location of an aquaculture site can have a profound effect on the impact that current, waves and tides have on the fish farm equipment and possibility for escapes due to structural failures. Aquaculture sites tend to be located close to shore. As waves approach the shore their energy begins to interact with the shallower seafloor. The wave velocity begins to slow down to a point where several waves may combine together (i.e., shoaling). The resulting wave length also decreases while wave height increases as their individual energies are compressed. Eventually the increased wave steepness can no longer be maintained and the wave breaks, typically when the water depth is about 1-2 times the wave height. Waves approach the shore in one of three standard ways dependent on the wave characteristics and seabed slope:

1. Spilling breaker – Occurs over a flat seabed as the wave crest spills down the front face of the wave while releasing its energy as it moves through the surf zone.
2. Plunging breaker – Occurs over a steep seabed as the wave crest steepens and plunges forward to release its energy quickly.

3. Surging breaker – Occurs over a very steep seabed but the wave crest never actually steepens to a point that it breaks but rather surges forward up a beach and its energy dissipates over time.

Obviously seabed characteristics must be considered when designing specific fish farm mooring and net pen components. The amount of energy transferred to the fish farm will be influenced greatly by the predominate breaker experienced at the site. Likewise, wave energy may refract or bend due to the presence of land features. In these cases, wave energy will increase especially near headlands compared to bays and coves with beaches. Fish farms located near a headland should be designed accordingly. Wave energy may also reflect off land features and create a confused more energetic sea state where incoming and reflected wave energy meet. These situations should be avoided by fish farm operations and simply moving the site a little further from shore might achieve this goal.

The ocean environment is quite complex. Waves and current rarely ever occur in isolation. In some instances, wind-induced waves, tides and underlying ocean current may all approach an aquaculture site from opposing directions. When wind driven waves collide with tide or current, the resulting wave may become higher and steeper. All fish farm deployments must be aware of these situations and be engineered accordingly to prevent structural damage, fish stress, mortality, and escapes.

CAUSES OF ATLANTIC SALMON FISH FARM ESCAPES

The previous section highlights the intricacies that need to be considered in the design of the physical components of an integrated fish farm system with clear recognition of site specific conditions and limitations. Incorporation of the required technology with a strong grasp of human resources and training, mandatory and voluntary Codes of Containment, industry Best Management Practices, and various levels of government regulation are collectively required to establish and improve effective containment systems. A holistic approach to total system design will also include appropriate involvement from oceanography, biology, and local fish farming experience to help eliminate the various causes of escape from fish farms and mitigate risks to the farm operation and receiving environment. Escapements can result from a lack of understanding or failure in regards to any one of these disciplines when establishing and operating fish farm sites, particularly in the marine environment.

The causes for farmed fish escape are complex and varied. In freshwater land-based facilities, the causes tend towards human error. In the case of saltwater escape, the causes primarily relate to the possible combination of oceanographic conditions at the site, structural integrity of the equipment deployed, and operational practices implemented by farm management and staff. Assigning percentages or a ranking to the reasons for global Atlantic salmon escapement is difficult given the general lack of reliable reports associated with the occurrences and numbers of aquaculture escape events. Creating cause-and-effect relationships are further impeded by the overall lack of accurate and detailed descriptions of specific instances where an unclear combination of events resulted in the escapes of fish. These difficulties are also evident within “reliable” reports in Norway and Scotland, which are considered the most extensive escape related data collected and shared by government authorities.

Jensen *et al*. (2010) analyzed fish escape statistics from the Norwegian Directorate of Fisheries as reported from farm operators. The paper described several broad categories of potential escape events from September 2006 to December 2009. The analysis indicated that the most prevalent causes of Atlantic salmon escape were the result of equipment structural failures (68% of all reported escapes), land-based related incidents (11%), farm operational failures (8%), external factors (8%), and for unknown reasons (5%). Reported structural failures occurred as a result of large storm events that may combine with farm component fatigue coupled with human error when initially installing the site or subsequently operating/maintaining its components.

A summary of reported fish escape data from Scotland is available on the Scottish Government website. As reflected in the dataset, Scottish authorities did not require a description of the cause for escapement until 2009. The reporting requirements were further refined in 2012 to include primary and secondary causes. Prior to this, the total number of Atlantic salmon escapes with each event was reported with no explanation as to why or how the escapement occurred. However, the official data for 2005 noted that the dramatic increase in mostly acute large-scale escapes in that year (492,335 of 510,840 seawater escapes) occurred as a result of "severe storms" that were experienced in the north and west of Scotland in January 2005. This clearly illustrates the importance of equipment structural failures to prevent Atlantic salmon escapes in Scotland.

During the 2009-2012 timeframe, there were a total of 506,000 saltwater and 59,492 freshwater Atlantic salmon escapes reported to the authorities by fish farm operators in Scotland. The primary causes for these escapes, as a percentage of total escapes for the consolidated period is provided in Table 3. The vast majority of reported events that allowed escape of Atlantic salmon from fish farms in Scotland occurred in saltwater compared with freshwater operations during the 2009-2012 period (23 saltwater instances compared with six in freshwater). In both environments, there were a greater number of small-scale events (66.67% of freshwater events and 73.91% of saltwater events) that resulted in <10,000 fish escaping. Although fewer in number, large-scale events had a greater potential for impact on the fish farm operation and the receiving ecosystem since the total number of escapes was greater (75.64% and 93.34% of escaping individuals were from large-scale events in freshwater and saltwater, respectively). These trends are consistent with operator escape reporting in Norway where small-scale events accounted for 81% of all instances but large-scale events resulted in 91% of the total number of reported escaped fish, primarily in saltwater operations (Jensen *et al*. 2010).

Table 3. Causes and numbers of Atlantic salmon escapes in the Scotland Atlantic salmon aquaculture industry during the period of 2009-2012 as reported by fish farm operators.

Freshwater		
Reported Cause of Escape	**Reported # Escaped**	**% of Total # in Period**
Hole in Net (Unknown)	0	0
Hole in Net (Predator)	43,927	73.83
Human Error	12,385	20.82
Equipment Failure	0	0
Weather	3,180	5.35
Total	59,492	100.00

Saltwater		
Reported Cause of Escape	**Reported # Escaped**	**% of Total # in Period**
Hole in Net (Unknown)	83,332	16.47
Hole in Net (Predator)	29,740	5.88
Human Error	13,262	2.62
Equipment Failure	1,092	0.21
Weather	378,574	74.82
Total	506,000	100.00

Table 4 further separates the official Scotland escape dataset based on the magnitude and cause for each event for both freshwater and saltwater operations. It is clear from the data that not every reported escape event has the same potential impact on the fish farm operation or the receiving ecosystem. The data in Table 4 also illustrates the need to understand the specific causes for escape before prioritizing solutions to the Atlantic salmon escape issue. For instance, in saltwater, human error is cited as the cause for 6 of 23 events (26.1% of all events) resulting in 13,262 Atlantic salmon escapes. This number of escapes should not be ignored but clearly human error in saltwater operations has a much smaller effect on escapes compared with weather-related losses that was cited as the cause in only 4 of 23 events (17.4%) but resulted in a staggering loss of 378,574 reported Atlantic salmon escapes from saltwater operations in Scotland during the 2009-2012 period.

Table 4. Summary of the scale and cause of events that lead to small- and large-scale escapement of Atlantic salmon from freshwater and saltwater fish farm operations in Scotland during the 2009-2012 period.

Type	Total number of events	Scale	Number of each event	Cause	% of total events	Total number of escapes
Freshwater	6	<10,000 escapes	4	Hole in Net (predators)	25	9,700
				Hole in Net (weather)	25	3,180
				Human Error	50	1,610
		>10,000 escapes	2	Hole in Net (predators)	50	34,227
				Human Error	50	10,775
Saltwater	23	<10,000 escapes	17	Hole in Net (Unknown)	12	6,766
				Hole in Net (Predator)	18	14,740
				Human Error	29	2,728
				Equipment Failure	29	1,092
				Weather	12	8,349
		>10,000 escapes	6	Hole in Net (Unknown)	33	76,566
				Hole in Net (Predator)	17	15,000
				Human Error	17	10,534
				Weather	33	370,225

Developing the most effective escape mitigation strategy would be possible if the various causes of escape could be ranked. Table 5 relates the number of escape events and resulting number of escaped Atlantic salmon to specific causes for escape from freshwater and saltwater Atlantic salmon farms in Scotland during 2009-2012. The Cause Impact Indicator (calculated by multiplying the proportion of total events with the proportion of total escapes for each cause) for each reported cause of escape provides insight into those causes that tend to be more important to understand and mitigate to provide the greatest return on investment from collective escape prevention efforts. From the Scotland Atlantic salmon data as reported by fish farm operators, ranking the Cause Impact Indicators of specific causes in freshwater results in Hole in Net (predators), Human Error, and Hole in Net (weather) while completing the ranking for saltwater escapes orders the causes as Weather, Hole in Net (unknown), Hole in Net (predator), Human Error, and Equipment Failure.

Table 5. The combined chronic and acute impact of reported causes for escape in freshwater and saltwater operations in Scotland during 2009-2011.

	Total Events	Total Escapes	Cause of Events	# Events	Proportion of Total Events	# Escapes	Proportion of Total Escapes	Cause Impact Indicator	Cause Impact Ranking
Freshwater	6	59,492	Hole in net (predators)	2	0.33	43,927	0.738	0.24354	1
			Hole in net (weather)	1	0.17	3,180	0.053	0.00901	3
			Human Error	3	0.50	12,385	0.208	0.10400	2
Saltwater	23	506,000	Hole in Net (unknown)	4	0.17	83,332	0.165	0.02805	2
			Hole in Net (predator)	4	0.17	29,740	0.059	0.01003	3
			Human Error	6	0.26	13,262	0.026	0.00676	4
			Equipment Failure	5	0.22	1,092	0.002	0.00044	5
			Weather	4	0.17	378,574	0.748	0.12716	1

Atlantic salmon farmers assign the number of fish to a specific cage based on the best estimate available at the time of stocking. Generally, the number of mortalities is tracked with a reasonably high level of confidence (except in times of unusually high acute mortality). However, the only accurate count of the number of fish stocked in a specific net pen occurs following removal of the market fish at harvest. Positive and negative population discrepancies between the number of fish stocked with the removal of mortalities and the number harvested can be expected given the lack of technology to accurately count individual fish at any stage in the grow-out cycle. This general lack of accurate stock numbers throughout the grow-out cycle also adds uncertainty to the total number of escapes from fish farm activities. In fact, the data tracking the number of total losses of Atlantic salmon in Norway also includes a category associated with “Counting Error,” which are used to adjust the total overstocked population by over 1.9 million individuals in just 2011. Population discrepancies also occur in the Newfoundland and Labrador context where population adjustments are required to account for inventory surpluses or shrinkages after a net pen is emptied due to harvesting or grading. This inherent level of counting discrepancy certainly suggests that many anticipated chronic escapes might involve fish that were never actually stocked. As an alternative, one may assume that some of the numbers of fish assigned to the counting error stock might have been actually stocked in the net pens but escaped at some time. This could have been due to any number of causes during the grow-out cycle and not accounted for until the final counting reconciliation was made following harvest/grading. The reliability of self-reported fish farm escape data must also be considered with some degree of caution since it is generally expected that the actual number of escapes go underreported. Furthermore, the actual occurrence of each acute or chronic escape event can go unnoticed for extended periods of time depending on the cause of the event. These conflicts illustrate the challenges associated with validating the number of fish that escape during any specific event or throughout the grow-out cycle, particularly related to small scale events that tend to be very difficult to trace or verify. These uncertainties also make it very difficult for farm operators and regulators to calculate specific returns on investment associated with specific mitigation measures. To this end, broad rather than surgical mitigation efforts are typically considered to address escapement from farm operations.

Other documented causes for Atlantic salmon escape from fish farms exist from a global perspective, but are not specifically accounted for in the Norwegian and Scottish escape reporting. This information, however, must be considered as a possibility when assessing risks from aquaculture escapes. For instance, vandalism of stocked net pens resulted in the escape of an estimated 100,000 Atlantic salmon in New Brunswick, Canada in November 2005. Despite all these shortcomings, the reported broad causes for escape from Norway and Scotland are reasonably consistent and provide a representation of the causes and magnitude of escapement from the fish farm operator's perspective and can be used to focus our collective attention to understand and mitigate chronic and acute losses in the future.

STRUCTURAL FAILURE

Freshwater operations

Theoretically, juvenile Atlantic salmon can move with production water through the entire hatchery production system and leave the confines of the hatchery to the receiving watershed if given the opportunity. The likelihood for chronic or acute escapement from hatcheries to local watersheds through the plumbing system diminishes as the level of filtration and water recirculation within the hatchery increases. Contemporary hatcheries tend to include advanced recirculating technologies including pumps, sumps, heaters/exchangers, and filters to gain control over water quality and quantity. Complete recirculating hatcheries would present little opportunity for juvenile Atlantic salmon to escape while using established standard operating procedures for the facility, which should also eliminate the possibility for escape as a result of human error. Flow through hatcheries still require filtration to clean effluent that generally exits the hatchery through a single pipe to return water to the local watershed. In these cases, mechanical filters are also likely sized such that effluent water will be stripped of the smallest eggs/alevins prior to release to the receiving watershed. Hatcheries located close to surface water systems also have the risk for possible flooding that may overflow hatchery tanks, especially those located outside, and the probability for escape of juvenile life stages increases dramatically as the floodwater recedes.

Not all freshwater operations involve land-based hatcheries, some juvenile Atlantic salmon production occurs in net pens in ponds or lakes. These operations have many similarities to marine net pen systems but with much less current and wave energy to contend with. Government statistics from Scotland indicate that nearly 74% of all freshwater escapes of Atlantic salmon are a result of holes in the containment net that are attributed to predators. Clearly, predator control measures similar to those used in saltwater production systems must also be implemented while operating net pens in freshwater.

Saltwater operations

Structural failures in saltwater operations are primarily associated with the interactions of waves and current on the fish farm infrastructure including the surface collar, smolt or grower nets and the mooring system. Structural failures can serve as a catchall category for losses associated with weather, hole in net (unknown), and equipment failure. The set represents a combined 56% of the total number of reported events and nearly 92% of the total number of reported fish farm escapes in terms of the reported losses in the Scotland Atlantic salmon farming industry and therefore have, by far, the greatest potential for impact from Atlantic salmon escapes.

Collar failure

As described, the predominant surface collar used throughout Atlantic Canada and specifically in Newfoundland and Labrador is manufactured of HDPE pipe. These collars are generally wave conformers and relatively transparent, and bend as necessary with passing waves. Maintaining the structural integrity of the surface collar is required to ensure that a complete system failure does not occur resulting in a fish escape. Surface collars may collapse if significant strain is experienced resulting in the circular collar becoming more elliptical until the collar collapses. Alternatively, localized buckling of the HDPE pipe may occur at the point of bridle attachment if the strain applied is too high for the structural integrity to sustain. Less frequently a collar pipe may break entirely, possibly allowing the foam plug within each pipe to be lost and water to fill the foam void within the pipe. This series of events will result in undesired system submersion that will allow fish to escape over time through the top bird net, especially given that the bird net mesh is almost always larger than the containment net mesh that is sized to retain the cultured fish stock. In addition, a collapsed collar or broken pipe sections present a risk for interaction (e.g., abrasion) with the containment net that can result in holes torn in the net mesh and possible fish escape through these net breaches.

While net/collar system transparency is desirable, in reality, a portion of the passing wave energy is transferred to the fish farm infrastructure, including the surface collar and upper portions of the nets that are located above the wave base. Hanke *et al.* (2013) characterized the wave energy transferred to fish farm infrastructure by comparing the expected significant wave height in the absence of a fish farm (calculated) with the actual significant wave height after the wave passed through a group of net pens (measured). The energy absorbed by the net pens varied with the tide and period of the incident waves but the data clearly illustrated the dampening effect that the fish farm has on passing wave energy. The comparative approach described ignored the loss of wave energy due to bottom friction and wave refraction as well as the influence of wind on the net pen components located above the water surface.

The HDPE collar pipe exhibits complex properties associated with its ability to behave like an elastic material and return to its original configuration or retain memory of the deformation after the load is removed, which might cause permanent damage. The most important factors affecting whether a HDPE pipe deformation is temporary or results in permanent damage include the load level, load rate and temperature. The effects from a steady load applied by tidal current and quick high loads from wave activity will have different outcomes to the surface collar due to these complex properties. The HDPE collar used in fish farms is located at the surface on a continuous basis and is frequently in place for an extended period of time (perhaps decades). Exposure of HDPE material to ultraviolet light is known to affect the stress at which its elasticity ceases (yield stress), the stiffness (modulus of elasticity), and the amount of stretch before the pipe breaks (elongation to break), with the impact dependent on the duration of weathering (Ollick and Al-Amir 2003).

These HDPE material properties are important within a fish farm setting as a continuum of loads and rates are experienced as innumerable cycles of wave and current energy are transferred to the surface collar, primarily at the bridle connection points with each passing wind event and tidal cycle. Failure of the collar can occur in higher energy conditions, primarily from strong current forces, which transfer loads that may force the circular surface collar into an elliptical shape. Stronger currents may transfer additional load to an elliptical collar until the surface collar collapses (i.e., the ellipse becomes flat). Alternatively, the surface collar HDPE pipes may collapse due to local buckling within the cross section of the pipe, particularly at the bridle attachment points along the surface collar. Fredriksson *et al.* (2007a) describes a series of modeling and field studies conducted to evaluate HDPE collars in fish farm settings (double ring 100 m circumference collar flotation pipe with 0.3238 m and 0.0198 m pipe diameter and thickness, respectively). Models were completed to estimate the failure loads of a surface HDPE collar when secured by a single bridle, two bridles extending from the same submerged grid plate to distribute the load, and two pairs of bridles that extend from adjacent corners of the submerged grid to further distribute the incoming load (Figure 6). The resulting failure loads associated with each bridle configuration is also provided in Figure 6.

Fish farm operators would normally never plan to use a single bridle to secure a net pen for an extended period of time. However, bridles extend to the water surface and are vulnerable to damage. If partially cut by farm vessel props, this would leave either a weakened bridle or single bridle to secure the collar. In these unfortunate instances, the failure load of the HDPE collar is estimated to be as low as 53.0 kN. The typical bridle-collar arrangement involves two bridles extending from the same submerged grid plate and in this case the failure load is nearly double to 98.6 kN. More than 444.0 kN was required before the failure load of the HDPE surface collar was reached when four bridles are properly arranged to secure the collar and positioned to receive the incoming energy. This amount of load can be measured regularly on fish farm sites during storm events; however, the actual failure load would be less than this as an incoming wave direction would rarely be oriented such that all four bridles extending from two adjacent submerged grid plates would distribute the load equally across the surface collar as suggested from the four bridle model. Hanke (2010) observed this to be the case based on inline load measurements taken from bridles that were connected to adjacent submerged grid plates similar to the four bridle model configuration. In Figure 7, the storm experienced on day 304 was incoming in a direction that it was measured in one corner of the submerged grid (graphs A/B) but not by the bridles extending from an adjacent corner grid plate (graphs C/D).

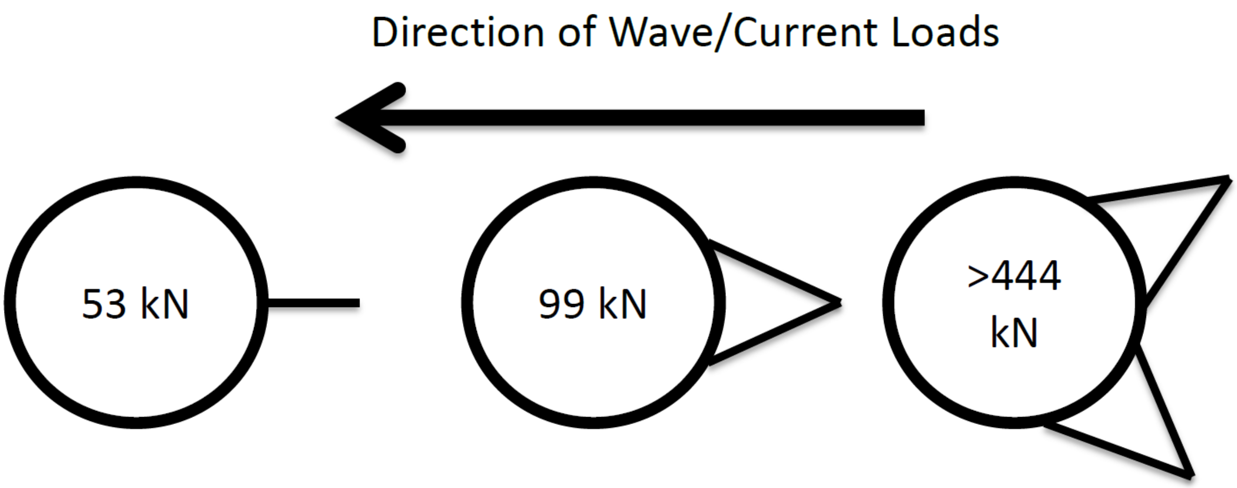

Figure 6. Estimated failure loads of HDPE collars used within the fish farming industry based on the number of bridles (one, single set of two, and two pairs of bridles) connecting the submerged grid system to the surface collar.

The Fredriksson *et al*. (2007a) models assume the bridles are symmetrically attached around the circumference of the HDPE collar. In reality this would rarely be the case and even balancing the two bridles that extend from the same submerged grid plate is difficult to achieve. Hanke (2010) measured similar loads in regards to timing and magnitude within a pair of properly balanced bridles (graphs A/B in Figure 7). However, bridles can experience dramatically different load forces from the same oceanographic event if the pair is not properly balanced (graphs C/D in Figure 7). As an example, a storm passing through the aquaculture site on Day 297 in Figure 7 was experienced by all four bridles but in the unbalanced pair the resulting load in one bridle (graph C) was measured to be more than twice as large as the paired bridle (graph D) despite the fact that both of these bridles are extending from the same submerged grid plate and therefore should be balanced to experience about the same load throughout this event (as was the case in graphs A/B). Fredriksson *et al*. (2007a) also completed a simulation given the possibility for unbalanced bridles in the four bridle scenario and the failure load decreased considerably but was still greater than 300 kN.

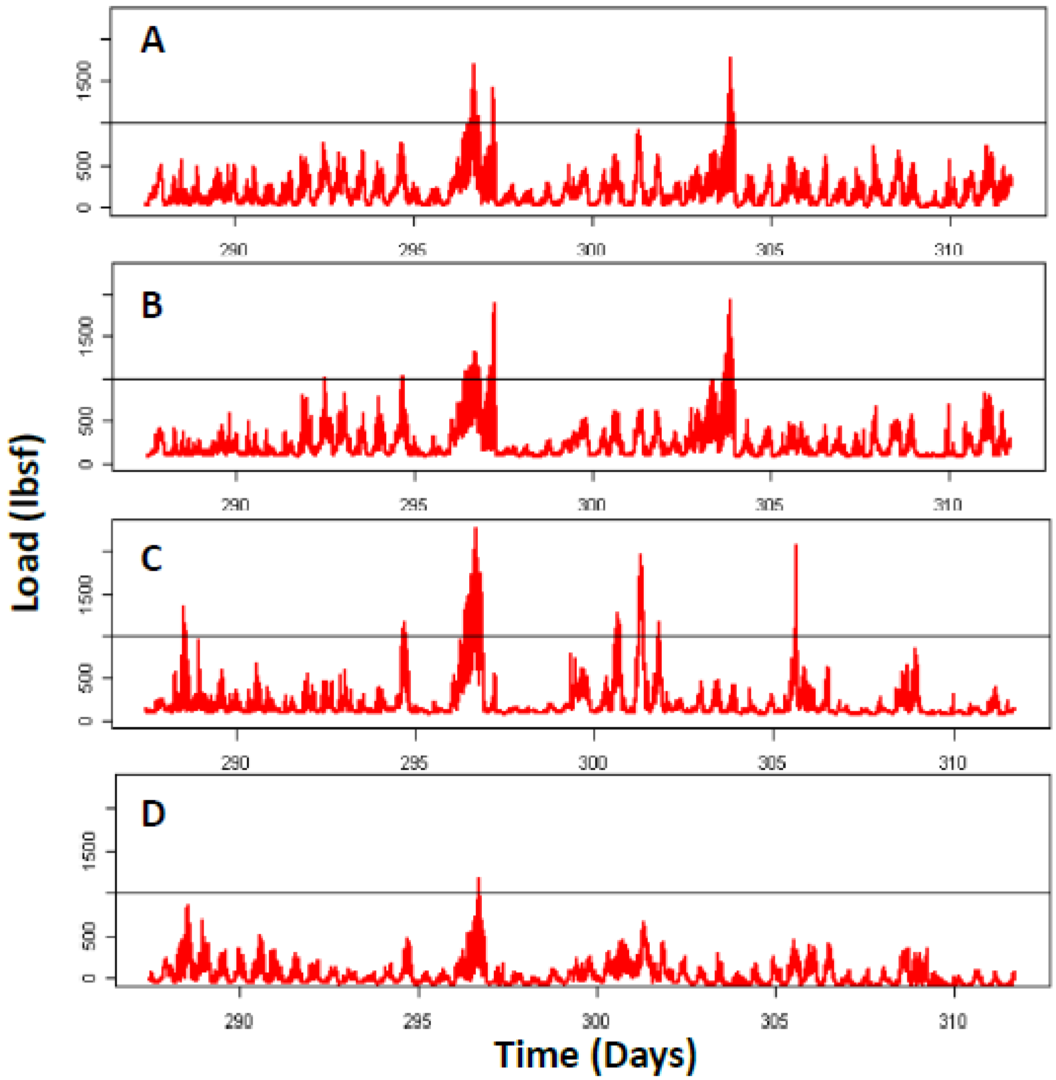

Figure 7. The synchronous loads (lbsf) measured from four bridles extending from two adjacent submerged grid plates to a single surface HDPE collar. Graphs A/B represents forces experienced by a bridle pair while C/D represents the adjacent bridle pair (Hanke 2010).

For comparative purposes, it is worthwhile to note that the maximum loads measured by Hanke (2010) were about 2000 lbsf and this is equivalent to less than 9kN and therefore considerably less than the model results discussed by Fredriksson *et al*. (2007a).

The oceanographic effects on the surface collar also affect the movement of the system both vertically and horizontally within the x-y plane that is defined by the grid cell lines. Hanke (2010) measured these collar movements on quite exposed fish farm sites in the Bay of Fundy, Canada to gain further insight on the additional stress experienced by the system that cannot be measured with load cells deployed on bridles alone. Figure 8 summarizes the horizontal displacement data collected from a single net pen by securing a DGPS receiver to the handrail (compared against a shore based immobile reference receiver). The starting location of the collar is represented by the cluster of positions to the left in Figure 8 while the ending position is represented by the cluster in the upper right of Figure 8. The net pen migration during a two-day storm event is represented by the track outlined between the starting and ending clusters of position. Net pens that are tied to the submerged grid system move very little within its grid cell as a result of normal oceanographic conditions, including tidal cycles, as seen by the tight clusters of horizontal movement before and after the observed storm event. This is apparently not the case during episodic storm events where the net pen movement can be quite evident. In the specific case shown the net pen did not return to its original position but rather remained in a new but shifted horizontal position following the storm.

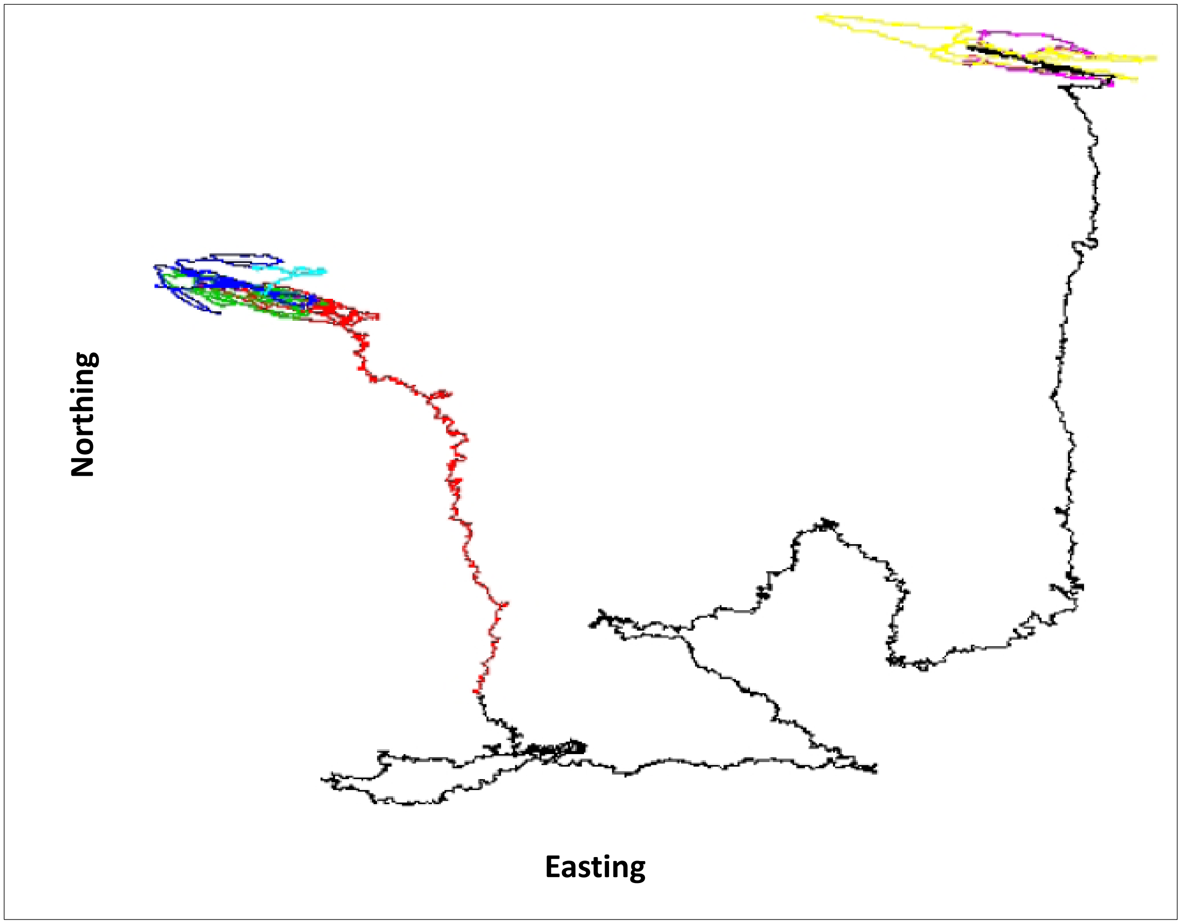

Figure 8. Horizontal displacement experienced by a typical net pen tied using the standard paired bridle method during pre-storm, storm and post-storm conditions in the Bay of Fundy, Canada (Hanke 2010).

Tide can also provide a considerable amount of force to the net pen system and specifically the bridles that must retain the net pen while not damaging the surface collar. Hanke (2010) also monitored the horizontal movement of net pens due to influences of the tidal cycle in the Bay of Fundy, Canada (Figure 9). The observed net pen migrated up to 25m in the north-south direction and 15m in the east-west direction over three tidal cycles. The flood and ebb tidal movements did not retrace itself. This can be expected as each tidal phase is unlikely to pass through the site from exactly the opposite direction given the influence of the surrounding land and seabed on tidal flow.

Additional concerns exist related to the structural integrity of the surface net pen collar. Vessel collisions with the net pen may occur from time-to-time. This may cause damage directly to the collar at the point of contact or cause permanent deformation at the point of bridle connection if the vessel collision loads persist and exceed the elongation to break the HDPE pipe. Vessels may also push the surface collar below the water surface and submerse the top bird net; however, the likelihood for fish escape in this manner is considered very low as the contained Atlantic salmon would almost definitely avoid the area affected while the vessel was present. Vessel operators may also choose to secure their boats to the surface collar during inclement weather and damage to the collar may result from the frequent loads that can occur during persistent wave activity.

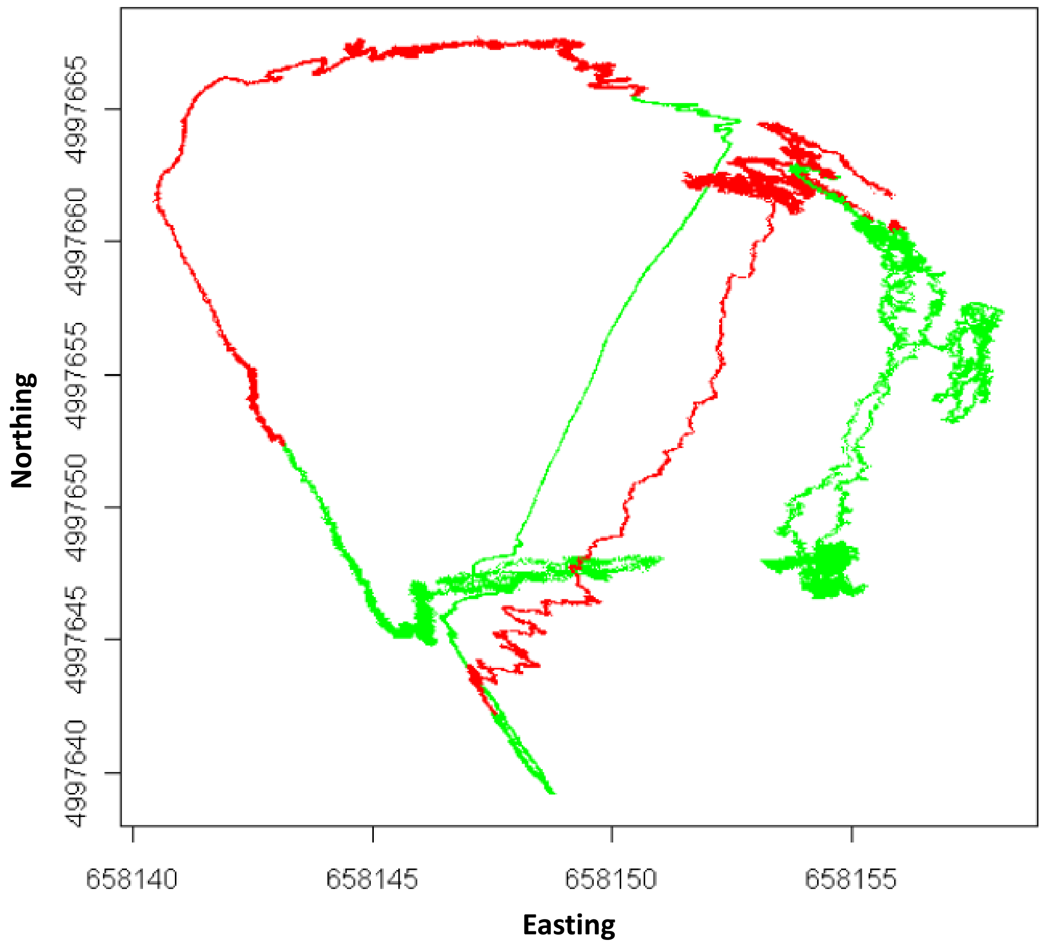

Figure 9. Horizontal migration of an Atlantic salmon net pen monitored in the Bay of Fundy, Canada over the course of three tidal cycles. The excursion track is colour-coded to illustrate the flood (red) and ebb (green) phases of the tidal cycle (Hanke 2010).

Finally, some Atlantic salmon farm sites may be located in areas that experience seasonal freezing spray or ice flows that interact with the site infrastructure. Freezing spray may occur in nearly all Atlantic salmon farming regions as the air temperature may frequently reach well below 0ºC and freeze water that sprays up onto farm infrastructure. The additional weight of this ice may break the handrails and give an opportunity for escapement if the jump net is lowered to the water surface thereby allowing Atlantic salmon to inadvertently jump out of the net pen circumference. Additional weight from ice build-up may also submerse the surface collar until the ice melts following submersion within the warmer seawater. Atlantic salmon could escape through the larger mesh bird net while submersed; however, the likelihood for escape to occur by this means is considered to be very unlikely unless feeding is occurring at the same time to attract the contained stock to the surface. Ice flows may increase the loads experienced by the bridles and surface collar and have been documented to cause issues with fish farm infrastructure in numerous jurisdictions in the past (e.g., Jensen *et. al.* 2010).

As noted earlier, the frequently used HDPE collar displays elastic and rigid properties. Both properties are load rate dependent and therefore the resulting deformation, if any, will depend on whether a specific load is applied slowly or quickly. Both rates are possible in environments in which fish farms operate as the described effects from storms are primarily due to passing waves that apply loads quickly and frequently during a specific event. Tidal loads would be applied slowly and over an extended period of time from the same direction before switching and coming from an opposing direction. The effects of these loads on surface collar structural integrity must be considered when planning a site and particularly the interface between surface collars and bridle connections.

It is obvious that locating sites in more exposed open ocean environments will result in larger forces being applied to the deployed grid and net pen infrastructure. Deployment of larger HDPE pipes would solve issues that arise from these increased forces. However, while simply deploying larger HDPE pipe might provide increased strength, this solution will also provide more collar buoyancy and in turn result in less wave transparency and even greater forces experienced by the collar that can ultimately result in the reverse effect, thereby increasing the potential for surface collar damage.

Net failure

As previously discussed, most Atlantic salmon fish farms consist of "gravity-type" net pens held on site with a subsurface mooring grid array. The pen is made with HDPE pipes formed in a circle that provides a floating surface structure so the containment net can be "hung" in the water column. Attached to the bottom of the net is a combination of either individual clump weights or a heavy ring to maintain containment volume. This system is able to retain stocked Atlantic salmon for an extended period as long as the gravity net holds its structural integrity. However, significant breaches in the containment net panels may result in substantial acute and chronic escape of Atlantic salmon from the net pens. The break strength of the net panel twine must be sufficient to withstand the environmental loads experienced at the site. Likewise, any opportunity for net entanglement with broken collars, other net pen components or external debris must be avoided to ensure the structural integrity of the containment net at all times. For these reasons, the containment net is arguably the most important component of the fish farm infrastructure as it is entirely responsible to physically hold the stock of Atlantic salmon.

The containment net is traditionally comprised of a series of net panels (or a single continuous net panel) around its circumference hung from numerous vertical rope downlines (traditionally polyester rope with nylon net) that provide structure to the mesh. Horizontal ropes are also integrated within each containment net along the perimeter at the top of the net (top line), water surface (waterline) and bottom of the circumference net panel (bottom line). These net pen details are important from a design perspective so that when properly deployed, environmental loads on the net panels are transferred to integrated vertical and horizontal rope components. Loops (commonly referred to as soft eyes) are often integrated at intervals along the waterline and used to secure the net to the surface collar. In this manner, the jump net that extends from the water surface to the handrail may remain slack during deployment as the weight of the containment net and any biofouling is buoyed by the surface collar and not the handrail. Similar soft eyes are typically located along the length of the bottom line to secure the containment net to the weight structure (clump weights or weight ring) to mitigate net bagging. The weight structure is also tied directly to the outside of the surface collar such that its mass is not actually buoyed by the containment net but rather the more structural surface collar. Also hung from the bottom line is the bottom net panel, which may be comprised of a series of pie-shaped panels that come together in the middle and are frequently secured to a steel ring or a single/multiple panels that make a solid net panel. In all cases, there are a series of cross ropes integrated in the bottom net to provide structure for the net mesh, similar to the downlines in the circumference net.

Proper selection of materials used within the containment net is critically important. Originally nylon net and polyester ropes were used almost exclusively to construct containment nets. The nylon net panels have a substantial amount of elasticity that "absorb" the hydrodynamic loads experienced by the net from the site current forces. Loads that are not absorbed are transferred through the polyester rope, which has less stretch, to the surface collar. Likewise, loads experienced by a net pen from passing waves are dampened by the surface collar but the resulting vertical motions in waves may transfer significant loads to the containment net that is primarily experienced by the polyester ropes that connect the net to the surface collar. In this manner, the nylon net and polyester rope components must "work together" to maintain the structural integrity of the containment net.

In recent years, new net materials have been introduced to the fish farming industry that are stronger than nylon. However, in many cases the new material has significantly less elasticity than nylon therefore requiring greater material strength to absorb the hydrodynamic forces. Likewise, the corresponding structural rope material also needs to be evaluated as an integral component as new net mesh material is considered. For instance, net mesh made of spectra will have greater strength when compared with nylon net but much less elasticity for the same twine diameter. If a containment net is made with spectra mesh and polyester rope (having more elasticity than spectra), it is possible that the polyester rope will stretch significantly more than the spectra net. In this situation, the spectra net could be the component that transfers the load and as a structural component, the spectra net will therefore have higher concentration stresses and may be more susceptible to failure.

The effect of currents and waves on the net is not entirely understood due in part to the complex relationships that exist and scaling issues when testing models in tank or field trials. Many of the recent efforts to characterize the hydrodynamic effects inside and outside of a net pen were reviewed by Klebert *et al*. (2012). The following list includes examples of the numerous approaches that have been developed to characterize the drag forces acting on net mesh by current and waves.

- Computer Modeling Approaches:
    - Bars of the net mesh are represented as individual cylinders and a Morison equation approach is used to calculate net drag (Tsukrov *et al*. 2000).
    - Finite element analysis used with consistent net elements applied to net panels that are larger than individual meshes but smaller than the entire net pen to determine fluid dynamic drag (Tsukrov *et al*. 2003).
    - Using the Tsukrov *et al*. (2000) and Tsukrov *et al*. (2003) approach, Fredriksson *et al*. (2007b) developed modeling techniques to assess large farm structure of gravity type net pens considering flow reduction through the farm.
    - Hydrodynamic forces calculated using lift and drag coefficients on super element components of a net panel (Lader and Fredheim 2003).
    - A lumped-mass model developed for the mooring and net of an entire net pen to estimate the effect of environmental forces on volume reduction (Huang *et al*. 2006).
- Tow Tank Scale Models:
    - Tow tank trials were used by Aarsnes *et al*. (1990) to develop drag coefficients as a function of solidity (clean versus biofouled net) and the angle of incidence of the incoming force.
    - Nets with different solidity were monitored in a wave flume to characterize the wave damping effect by these nets (Lader *et al*. 2007).
- Field Studies
    - Full scale field studies are rare but have been completed in some instances. For example, Lader *et al*. (2008) correlated observed net deformation in two full-scale Atlantic salmon net pens to measured incoming currents.
    - The Fredriksson *et al*. (2007b) approach also considered measured forces on a farm system with different clean, smolt and fouled net characteristics.

Numerical modeling and tank/field trials provide insight into the effects of currents and waves on the loads transferred to the containment net structure. Uniform current will act on the net through drag and lift hydrodynamic forces, which are proportional to the squared current speed and the total net area exposed to the current. Obviously, a larger circumference net pen with a deeper net will have higher hydrodynamic forces acting on the containment net compared with a smaller circumference and shallower net pen in a uniform horizontal current. Of primary concern, resulting net deformation and deflection from waves and current may significantly reduce the volume available within a net pen by bowing the front circumference panel of the containment net inwards and lifting the bottom net towards the water surface (Figure 10). Bowing of the back circumference panel outwards will increase the volume, however, the outward deflection of the back panel will be smaller than the inwards deflection of the front panel as the incoming current will diminish as it passes through the front panel (and fouling) and the fish biomass (Figure 11). In fact, Aarsnes *et al*. (1990) reported that up to 80% of the net pen volume may be lost when the net pen experiences a current velocity of 1 m/s (approximately 2 knots), dependent on the suspended weight system present.

Fish farm operators recognize this net deformation issue and have made attempts to minimize deformation by adding weight to the bottom of the gravity-style containment net. However, even with weight added, farm operators may visually see deformed net panels bowing outside of the surface collar. In high current conditions, the weight ring may approach the water surface. Indeed, Lader *et al*. (2008) monitored deployed net pens with Atlantic salmon and reported volume reductions of up to 20% and 40% in 20 cm/s (0.39 knots) and 35 cm/s (0.68 knots) current velocity, respectively, despite having weight installed on the containment net to hold the bottom down. Significant loss of volume presents important fish welfare challenges to the fish farm operator as the stocking density becomes critically high, oxygen depletion will be rapid while stressed, and abrasion against the net or adjacent Atlantic salmon will be difficult to avoid. From an escape perspective, the likelihood for entanglement or abrasion of the containment net against the downlines that attach to the weight ring increases dramatically while deformed to this degree. Likewise, deformed containment nets will have the upper net sections very close to the water surface where entanglement with vessel props becomes a possibility. These instances may result in significant holes to the containment net that may lead to an acute or chronic escape if the damage is not mended in a timely manner.

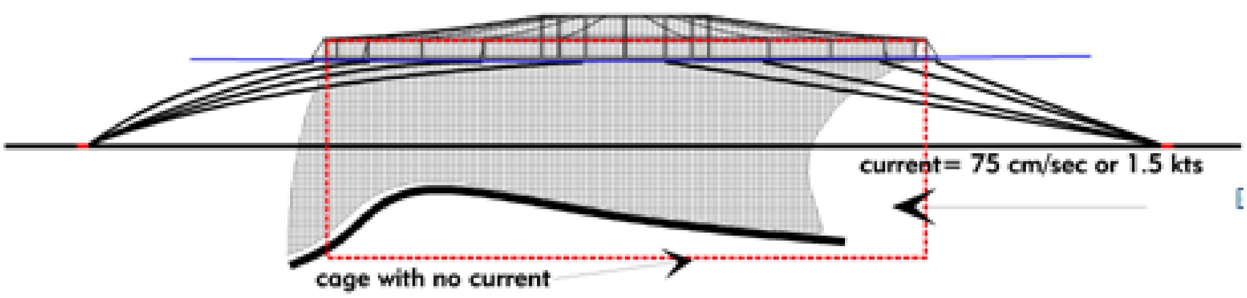

Figure 10. Estimated configuration of a containment net and volume available for stocked fish in no current and 75 cm/s (1.5 knots) current (drawn by P. Dobson).

Net deflection and deformation in current and waves will also increase stress on the containment net that may lead to a structural failure of the mesh. In low current environments (e.g., slack tide), the net deflection is negligible and the weight and resulting stress remain constant over the entire depth of the containment net. As the current and subsequent deflection increases, the stress from the weight still remains nearly horizontal in the deepest part of the net but the stress from the forces of drag, lift, and gravity increases closer to the water surface. The result is that the containment net near the surface may be positioned nearly horizontal at the point of connection to the surface collar. This arrangement provides far greater stress in the upper portion of the containment net compared with the portions of net panel at depth (Figures 12 and 13). Greater net deflection also results in less drag force applied to the entire containment net due to less total surface area exposed to the incoming current during deformation. Farm operators must consider this balance when deploying fish farm infrastructure to maximize growing volume and fish welfare while ensuring that all net pen and mooring components have sufficient strength to withstand the anticipated environmental loads on the specific site. Otherwise a complete system failure may result with substantial acute escape occurring.

Aquaculture infrastructure placed in the marine environment will attract fouling organisms through a community succession process similar to any other structure placed in the ocean. Biofouling of aquaculture nets is well documented and accepted, costing the industry a considerable financial sum to control and manage (Hodson *et al*. 1997). Despite the best efforts of industry to minimize biofouling, often by using anti-foulant net treatments, these strategies simply delay the onset of fouling community succession before fouled nets must be cleaned to maintain a healthy stress-free Atlantic salmon stock. The vast majority of net drag research does not consider increased solidity from biofouling; however, from a structural failure perspective, biofouling of the aquaculture net may add considerable weight to the entire net pen system and increases the solidity of the mesh opening potentially to the point where the net is effectively a solid structure that allows very little water to pass through. Swift *et al*. (2006) compared net drag results after towing clean and biofouled net panels at normal incidence to the current. They reported that the resulting drag of biofouled nets may be more than three times the drag experienced by clean nets (Table 6). Further, the resulting solidity from the biofouling and amount of biofouling growth were both positively correlated with the calculated drag coefficient of the net panels. However, the reported data showed a weak positive correlation with a large amount of scatter in the data that the authors attributed to the specific species involved within each biofouling community. This hypothesis has sufficient merit to warrant additional research given that many biofouling species would react in a relatively transparent manner with the passing current (e.g., algae, hydrozoans) while other species would provide a greater degree of solidity (e.g., solid organisms such as mussel spat).

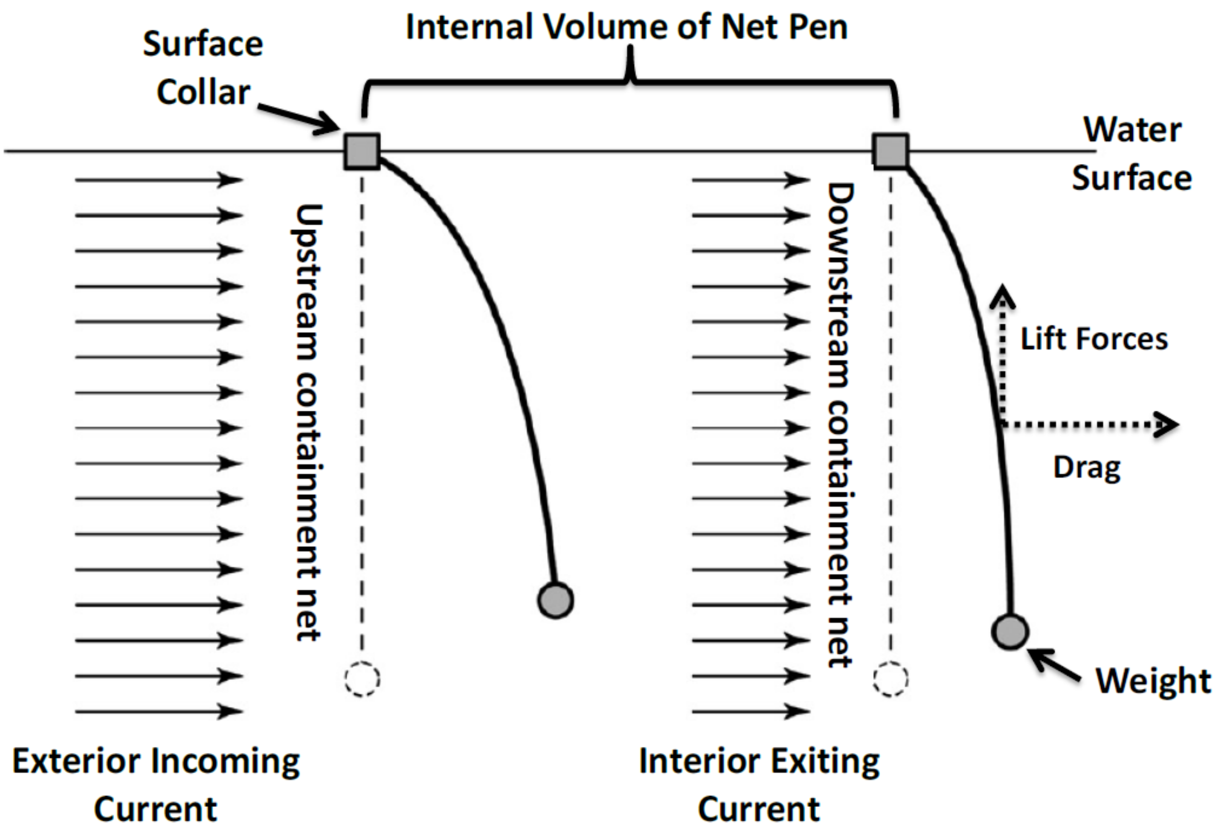

Figure 11. Differential deflection of the containment netting between the upstream and downstream containment net after the current passes through the leading net panel, biofouling and fish stock (adapted from Lader et al. 2008).

Table 6. Comparative effect of biofouling (74.3% solidity) on approximate drag force (N) of a net panel versus a clean net panel (12.1% solidity) (Swift et al. 2006).

	Approximate Measured Drag (N)			
Current Speed (m/s)	Frame Only (no net)	Clean Net	Biofouled Net	Biofouled Net % Increase over Clean Net
0.3	9	15	35	233
0.4	12	25	60	240
0.6	27	58	105	181
0.8	42	100	250	250
1.0	70	160	350	219

The bottom net of each net pen is also vulnerable to structural failure due to surface wave activity despite usually being located below the wave base. The bottom net is tied to the weight ring, which in turn is tied to the surface collar. In ideal conditions, the wave height and period would allow synchronous movement across the surface collar-weight ring-bottom net arrangement. However, the ocean is unpredictable and ideal conditions may rarely occur. In such cases, the bottom net may move asynchronously with the surface wave and collar activity (Figure 12). These conditions would transfer a significant amount of energy to the middle of the bottom net and may result in a complete structural failure at this location. Escape of Atlantic salmon stock from a large hole in the bottom net panel may be quite large given that the fish will remain deep within the net pen during storm events and may swim through the bottom hole as the net pen rises and lowers with each passing wave.

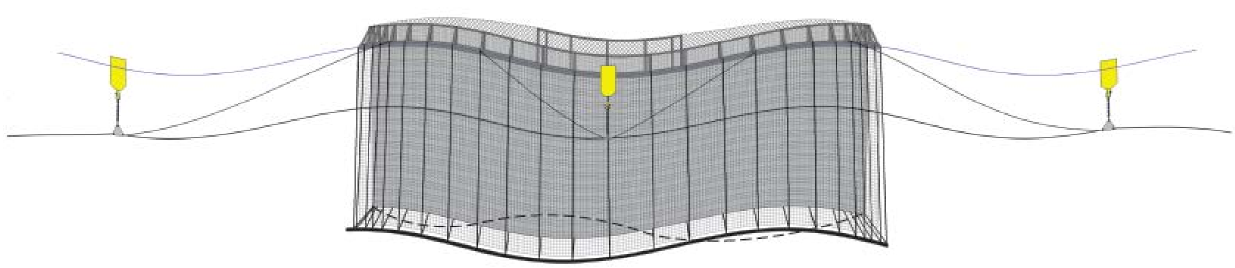

Figure 12. Relative movement of the surface collar-weight ring-bottom net components of a net pen during storm conditions. The bottom net would ideally move in rhythm with passing waves (dotted line) but may also move out of rhythm and cause violent motions of the bottom net that may lead to a significant structural failure and escape of stock (drawn by P. Dobson).

Mooring failure

The mooring system is essential to hold the group of net pens spatially and an important component to work properly to ensure the structural integrity of each net pen is not jeopardized. In most near shore applications where tidal currents are prevalent, Colbourne and Allen (2001) concluded that mooring loads at fish farm sites were not correlated to wave action but rather likely resultant from tidal current forces. Similar results were evident in Fredriksson *et al*. (2007b). In more exposed locations, however, it is possible for wave loads to represent a substantial component of the total force on the structure (Fredriksson *et al*. 2005). This work also indicates that in areas with both waves and currents, the velocities associated with each can combine in a nonlinear manner.

These results may be expected, given that the vast majority of net pen infrastructure is located below the water surface, and illustrate the need to determine the compounding effects of waves, tidal currents and wind forces anticipated at any aquaculture site while designing the appropriate mooring system. Anchor lines are typically connected directly to the gravity net pen system through the bridles that are tied to the surface collar. The point load forces from this connection have already been discussed in the Collar Failure section and will not be revisited here. Break load limits for the various components of each anchor line are generally available from the supplier at the point of sale. Further, engineering analyses are well established to design mooring systems for fish farm installations based on years of experience and inclusion of a reasonable safety factor to account for extreme oceanographic conditions and component fatigue over time. Still, mooring line failure may occur within marine fish farm installations. The damage to the structural integrity of the system may result in escapes of Atlantic salmon, especially if components of the broken anchor line become entangled with or cause abrasion to the containment net.

A more frequent issue with deployed mooring systems involves slippage of specific anchors. Each anchor line must be able to withstand the drag forces resulting from the aquaculture net pen within the maximum current and wave conditions anticipated for the site. These forces will be higher for smaller mesh smolt nets compared with grow-out nets. Biofouling also increases the drag forces compared with clean nets. Globally, some operations do not involve professional engineering services to design the required mooring system for a specific site, but rather rely on internal experience even while moving their operations to more exposed locations. This strategy has the potential to grossly underestimate the drag forces involved on new sites, particularly if site specific oceanographic conditions have not been measured, and deploying mooring components that will not withstand the environmental loads. For instance, concrete block dead weights are still frequently used to hold some fish farms; however, sites are progressively moving into more open ocean conditions where slippage of the concrete blocks may be expected. Anchor lines held by concrete blocks that slide along the seabed under high current conditions will result in a condition where not all anchors are holding a similar amount of the total farm drag force, and subsequent mooring structural failure may result as the loads experienced by adjacent anchor lines exceed their design capacity. Similarly, rock pins and drag embedment anchors may also fail if the actual loads exceed the design criteria for specific anchor lines. The resultant effect of extreme mooring line failure is that the net pens will be held on one side or the other by the working anchor line, potentially creating a devastating point load and pulling the cage into an oblong form, eventually kinking the collar, and resulting in a potential escape event as described in the Collar Failure section.

OPERATIONAL FAILURES

Freshwater operations

Statistics from Scotland show that more than 20% of freshwater escapes are reported to occur as a result of human error. Better training of hatchery production staff coupled with development of hatchery specific Hazard Assessment Critical Control Point (HACCP) plans and husbandry practices are expected to help reduce juvenile Atlantic salmon escapes due to human error. There are many documented uses of HACCP plans in food production and an increasing use of HACCP planning associated with aquaculture operations to mitigate escapement of target species. These efforts should be extended to also cover the freshwater production stage within commercial hatcheries. A HACCP plan is required within the Maine (USA) Containment Management System (CMS) that was adopted by the local Atlantic salmon farming industry in 2002, which requires inclusion of freshwater production facilities (Bureau of Land and Water Quality 2014). Identifying specific hatchery critical control points will focus management efforts to develop appropriate standard operating procedures and staff educational opportunities to mitigate stock escapement. Increasing staff education might also include recognition that intentional release of surplus hatchery-reared juvenile Atlantic salmon to local watersheds is not helpful to rebuild local salmon stocks as is frequently thought to be the case (Carr and Whoriskey 2006).

Saltwater operations

Numerous critical control points exist that may influence the opportunity for chronic or acute Atlantic salmon escape from the marine net pen infrastructure in typical saltwater fish farming operations. These points have been identified in numerous past efforts completed by industry associations and government agencies to develop voluntary or mandatory Codes of Containment. The resulting Codes of Containment are implemented by most companies in the form of standard operating procedures. Specific critical points important to consider for Atlantic salmon escape may be broadly grouped as either Fish Handling or Farm Procedures (Table 7).

Table 7. Critical operational points for the potential of Atlantic salmon escape.

Broad Operational Categories	Specific Potential Escape Vectors	Possible Frequency of Occurrence	Chronic or Acute Escape	Possible Number of Net Pen Escapes per Event
Fish handling	hatchery smolt transfers	once	chronic → acute	up to entire truck load (0-40,000)
	weight sampling and sea lice counts	monthly	chronic	up to entire sample (0-30)
	grading and splitting populations	once	chronic → acute	up to entire stock (0-120,000)
	fish health treatments	monthly	chronic → acute	up to entire well boat load (0-40,000)
	harvesting stock	once	chronic → acute	up to entire harvest number (0-50,000)
Farm procedures	net changes	0-3 times	chronic → acute	up to 50% of Stock (0-60,000)
	securing vessels to net pens	daily	acute	up to entire stock (0-120,000)
	towing of net pens with stock	0-2 times	chronic → acute	up to entire stock (0-120,000)
	diver entry for mort removal or stock inspections	weekly	chronic	low likelihood for large escape (0-1,000)

Fish handling

Fish stock handling is required throughout the production cycle. Most operators, however, limit the number of handling steps to reduce unnecessary fish stress that may trigger a fish health issue. Fish handling steps that typically occur during the Atlantic salmon production cycle include:

- **Hatchery smolt transfers** – The first handling step often involves the transfer of smolt to live haul trucks at the hatchery followed by one or more additional transfers until the smolt are delivered to the net pen, although transfer directly from hatcheries to well boats is also possible in some regions. These transfers typically involve hoses that are securely connected to the truck/tank using appropriate fittings. The final transfer will involve delivery of the smolt to the waiting net pen through the end of a hose that extends into the contained net pen volume.

  Fish escape is always a possibility during these transfers. Often the initial transfer to a live haul truck will have limited impact as escaped fish at this point will likely only fall to the ground at the hatchery near the receiving truck. However, this would not be the case if the escaped salmon finds itself to a nearby waterway allowing the fish to survive. All later transfers, including truck to vessel or directly to the net pen, will be completed near receiving local waters and recapture of escaped fish from these transfers is highly unlikely. Live haul trucks and tanks frequently have flow control valves that may be closed in the event of a connection issue with the pipe to the truck/tank. These transfer tanks can hold live fish for an extended period of time giving an opportunity for staff to repair any issues with the hose or connection fittings. Clearly, employing conscientious staff to complete these transfer steps is very important to mitigate fish escapes and especially to prevent a periodic chronic loss opportunity from becoming an acute event that might include thousands of individuals.

  The greatest risk for escape during smolt transfer to net pens actually occurs as a result of transferring smolt that are too small for the containment net mesh. The smolt are generally leaving a confined tank environment that is well stocked (at least 40 kg/m^3) and an established schooling behaviour is evident within the population. Smolt are transferred to marine net pens that are dramatically larger in size resulting in a considerably lower initial stocking density (< 1 kg/m^3), especially if the population is single stocked. Time is required, on the order of days, before the population begins to properly school within this larger and more energetic environment. During this time, swimming of individual Atlantic salmon may be rather erratic and the ability of the net to properly contain these smolt within the net pen environment is critically important as otherwise wayward individuals will simply swim through the net mesh and escape to the local waters. Smolt are generally transferred on the basis of average weight within the population; however, full confinement within a net pen is based on the minimum size of individual fish. Fish size will follow a normal distribution within a population. As such, half of the population will have a weight less than the average weight and risk escape if entered into a containment net having mesh size that is too large. Hatcheries tend to size grade the population frequently to optimize fish growth by keeping similar sized individuals together to compete for food resources while population runts tend to be culled due to poor performance that is expected to continue throughout the grow-out cycle. These practices result in a more narrow size range within each tank population so that the tails of the normal distribution curve will be small giving a tighter size range within each tank. A final size grading typically occurs prior to the time for saltwater transfer and helps to prevent escape through large net mesh. Understanding the size range of smolts, and in particular the minimum smolt size to be confined by the containment net mesh size will help to prevent escapes that are unlikely to be accounted for or reported.

- **Weight sampling and sea lice counts** – During the grow-out process, fish farm operators must periodically sample the stocked Atlantic salmon population to determine fish growth (to adjust feed rates), assess overall fish health, and determine sea lice counts. Sampled numbers are quite small compared with the total population within each net pen (involving as few as 30-50 fish per net pen) and therefore individuals can be sampled using a dip net. Fish taken as a sample have ample opportunity to flip out of the dip nets and escape but clearly the possible numbers involved would be quite low, therefore only representing a possible small-scale chronic event.

- **Grading and splitting populations** – Some Atlantic salmon farm operators still multiple-stock their net pen population during initial entry and require stock splitting at a later date to prevent crowding and subsequent environmental and fish health issues. Stock splitting may be accomplished by dropping the containment nets of the holding and receiving net pens and lacing these nets together underwater to create a swim tunnel under both adjacent surface collars. The opposite side of the holding containment net is lifted to shallow the net pen water depth to entice the fish population to swim towards the swim tunnel. This operation continues until the site crew determines that the initial population is split such that both the holding and receiving net pens contain approximately half of the total population each. Splitting a population of Atlantic salmon in this manner introduces a high degree of inherent risk for an acute escape to the local water. In this situation escape may occur if:

- holes are present in the net, of which the crew is unaware, that allow escape as the fish are corralled tight to the containment net;
- the swim tunnel is not properly laced;
- the operation proceeds during marginal weather that affects the outcome of the transfer;
- a fish health concern arises (such as low dissolved oxygen in the corralled stock if the nets are heavily fouled) and the operation must be hastily aborted increasing the likelihood for escape; or,
- the attending staff are not paying sufficient attention or miss the appropriate training and an opportunity for chronic leakage becomes an acute event with the possibility for a large number of escapes.

Grading Atlantic salmon may occur independently or coupled with splitting a multiple-stocked population. Grading requires that individual fish are taken from the net pen using a Braille net or fish pump and delivered to a grading table that sorts individuals by size. Atlantic salmon having a common size range are returned to specific net pens through a series of directional troughs and lengths of pipe that are secured to the grading table outlets and extend to each receiving net pen. Fish pumps allow the operation to proceed in a more fluid manner with a constant flow of fish while Braille nets move smaller numbers of fish within each discrete load. Both methods present opportunities for Atlantic salmon escape but possibly with a lower number of escaped fish using a Braille net. Vigilance to ensure that all pipe connections are secure or the integrity of the Braille net or various pipes are not jeopardized in any way is necessary to prevent escape.

- **Fish health treatment** – Bath treatments, used primarily to combat sea lice infestation, is becoming commonplace within Atlantic salmon operations globally. Presently, bath treatments that wrap the net pen with a tarpaulin occur less frequently, with the use of well boats to complete bath treatments becoming more common. Fish pumps are always used to move Atlantic salmon from net pens to holding tanks on the well boat for treatment. In theory, the fish are fully contained during the entire transfer and treatment process, thus limiting the opportunity for escape. In practice, issues might arise with the structural integrity of the transfer pipe or secure connection of the transfer pipe to the well boat tanks that may allow a chronic escape event to occur. Awareness of these possibilities and a full understanding of the operating procedures, primarily with the fish pump, can allow for the Atlantic salmon transfer to be stopped in the event that an issue arises. A small problem that results in the loss of a few fish could spiral out of control and result in a larger escape event if the crew panics and makes a series of wrong choices which could exacerbate the situation.
- **Harvesting stock** – Harvesting stock occurs when the Atlantic salmon reach the target weight to meet market and processing size demands. The methods used to harvest Atlantic salmon from net pens are essentially the same as those used to remove fish for grading and treatments, including fish pumps or Braille nets. The same potential issues are present regarding the structural integrity of transfer pipes and Braille nets and the connection of transfer pipes to harvest tables. The primary difference at harvest is that every escaped Atlantic salmon will cost the farm operation significantly more in financial terms given that the fish are now raised to their maximum target size and the potential risk to the receiving ecosystem could be higher having to deal with larger market sized escapes.

Farm procedures

Numerous farm procedures must occur frequently over the course of a grow-out cycle but which do not require the direct handling of fish. However, some procedures are recognized to have greater potential for escape of stock. The following list outlines some of these procedures.

- **Net changes** – Biofouling of aquaculture infrastructure cannot be avoided while using standard nylon net material. Growth of fouling organisms can be retarded for a limited time if the operations are using nets that have been dipped in an appropriate anti-foulant treatment. The traditional method to address net biofouling in Atlantic salmon operations involves exchanging the fouled net for a clean net while retaining the fish stock (cleaning the nets while deployed is becoming more common in some jurisdictions in recent years). Net changes require several steps to proceed without incident including:
    - Divers untie the fouled nets from the weight ring or clump weights if they are present and these weights remain at depth tied to the surface collar.
    - At the same time, the ropes that secure the containment net soft eyes to the surface collar at the water line are removed.
    - New clean nets are rolled over the handrail so they are positioned between the surface collar and the fouled net. The fouled net with the fish stock remains inside the clean net.
    - The clean net is pulled under the fouled net and to the surface such that the clean jump net is positioned inside the collar.
    - The fouled net is removed from the net pen surface collar using a maintenance barge equipped with a crane or net roller having sufficient capacity to handle the weight of the soaked containment net with excessive biofouling.
    - The new clean net is secured to the surface collar float pipes using its soft eyes along the water line and tied to the weight ring or clump weights at depth by divers.

  The process to change fouled nets while containing the fish stock is well established globally and typically occurs without incident or escape of Atlantic salmon. However, the primary concern with regards to escapes is to ensure that the site crew have ample opportunity to complete all steps before foul weather is experienced at the site. Otherwise, an unsecured containment net might need to be left unattended during storm conditions and the likelihood for escapes to occur increases dramatically if the containment net is not properly secured. The tide schedule also needs to be considered when determining the time required for net changes as pulling and securing the clean or fouled net is increasingly difficult while tides are running through the site.

  The possibility for Atlantic salmon escape from net pens is greatest after the containment net is changed rather than during the actual net change procedure. Typically, the farm operator takes advantage of the required biofouled net exchange to also increase the containment net mesh size within the new clean net. The primary advantage to increasing the mesh size is that more oxygenated water is allowed to pass into the containment net with less occlusion from a larger mesh size. A primary advantage to the farm operator at the time of a net change is that the schooling behaviour of the Atlantic salmon is usually well established. However, erratic swimming behaviour by individuals might still occur if the population feels threatened by the presence of a predator outside of the net or a storm/high current pushes the population closer to the containment net. A greater potential for escapes exists if the population has not been size graded prior to the net change with a larger mesh as the smaller fish within the population may fit through the netting. As with smolt transfer, it is important that the minimum size of fish is known to ensure complete containment following a net change to a larger mesh.

- **Securing vessels to net pens** – Vessels of various sizes frequently visit individual net pens throughout the grow-out cycle to complete any number of required tasks. These vessels might include feed vessels that visit each cage up to three times daily, maintenance barges that visit each cage as necessary to complete tasks such as change nets, and larger well boats or harvest vessels that visit each net pen to complete sea lice bath treatments as required and harvest the Atlantic salmon when they reach the target market weight. The primary concern with vessels around fish farm infrastructure is the possibility for entanglement and damage from vessel propeller(s). Holes may occur in the containment net due to entanglement with propellers, especially if the net shape is deformed or “bagging” from the effects of tide and current. Likewise, approaching propellers may draw slack net into the propeller wash and cut holes in the material that might allow fish to escape. Propellers may also cause partial damage or cut through net pen bridles, especially near the surface where they attach to the floating collar. When bridle lines are compromised an uneven distribution of loading on the surface collar may occur, damaging the structure. This damage could lead to net pen failure and therefore an extensive acute fish escape event.

Securing vessels to the surface collar is almost always necessary to prevent the vessel from drifting away from the net pen while work is underway. The likelihood of severe damage resulting from securing a vessel increases as the vessel size increases. Damage from securing vessels also increases significantly in high wind or tide conditions that will place additional strain on the fish farm equipment to hold the secured vessel in place. The resulting damage to the handrail or surface collar float pipes may provide a means for escape over a less effective jump net and through the larger mesh of the bird net.

It is often more difficult to visually observe the position of net pen components during manoeuvring when operating larger vessels. This situation may be exacerbated by the greater effect that wind will have on the position of larger vessels and potentially push the vessel into farm equipment even if bow thrusters are present. Collisions may result with the surface collar in the absence of appropriate visual contact. Large vessels may push the surface collar underwater to a depth that the jump net is rendered useless to prevent escape of Atlantic salmon that happen to jump out of the water in the direction of the submerged portion of the surface collar. Resulting damage from collisions may also break handrails. Broken handrails cannot support the jump or bird nets, providing openings through which fish may escape.

- **Towing of net pens with stock** – Operators in some jurisdictions tow stocked net pens for a variety of reasons including seasonal avoidance of ice or response to a fish health issue and bath treatments in nearby freshwater estuaries/rivers. Net pen towing requires considerable attention to detail to ensure that the stock arrives at the destination unharmed and without escape. The primary concerns during towing relate to the security of the connection between the net pens and the tow vessel, additional strain placed on the containment net under tow that might cause structural failure leading to possible escape, and entanglement in debris along the tow route that might result in a tear in the containment net and provide an opportunity for escape. Contingency plans are usually necessary for towing events but vigilance of the vessel crew to constantly monitor the operation is critical to ensure that escapes are not occurring along the way, which might go unnoticed until the net pen arrives at its destination.
- **Diver entry** – The use of divers within net pens may be replaced to complete some tasks (i.e., removal of dead fish) but it is difficult to find an alternative means to visually observe the stock for fish health concerns. The jump net must be untied from the collar handrail and lowered to the water surface to allow diver entry and exit from the net pen. In these instances, a dive tender is nearly always involved and will temporarily secure the jump net while the diver remains within the net pen. The likelihood for escape remains exceptionally low if the jump net is indeed temporarily secured in this manner but will increase if this exercise is not completed. The jump net must be properly secured to the handrail after the diver exits each net pen to ensure that the jump net does not drop to the water surface while the net pen is unattended, which would significantly increase the likelihood for chronic escapes to occur.

BIOLOGICAL FAILURES

Biological failure predominately occurs as a result of successful predator attacks to the net pen from above and below the water surface to gain access to the contained fish stock. Active predators above the water surface include various bird (e.g., cormorants, common gulls and falcons/eagles) and mammal (e.g., otters and mink) species. Aerial predators are generally attracted to stocked Atlantic salmon that swim close to the water surface, and especially those that are weak and moribund. Mammalian predators are initially attracted to the farm infrastructure. Both predators can also be “baited” to less organized operations that improperly store feed supplies and dead fish that produce an inviting scent. Birds and mammals that frequent aquaculture sites become accustomed to the noise and activities from farm operations and over time may become more difficult to dissuade.

Each net pen is typically fitted with a top bird net that extends over and protects the water surface within each net pen from aerial avian attacks. The top bird net provides no containment benefit for the majority of the grow-out period as the fish could easily swim through the larger bird net mesh should the net pen submerge as earlier discussed. However, bird nets are often removed if a risk of excessive ice build-up is eminent from freezing spray. Bird nets are also typically removed at the beginning of harvesting to minimize the time required to remove the bird net before daily harvesting begins. Acute escape of fish from bird predation is unlikely, but low numbers of chronic escape may occur. For instance, captured fish may be released from the talons or mouth following a successful predatory attack and the Atlantic salmon falls to the water outside of the net pen circumference. Predatory mammals from the surface tend to be clever and able to work through compromised net mesh and knots to gain access to the contained fish. These predatory attacks may create holes in the containment net, but again, acute escapes are highly unlikely as the holes tend to be located above the water surface in the jump net and possible chronic losses would involve very few numbers.

Aquatic predators (such as seals, tuna, and sharks) can be large and powerful, potentially inflicting significant damage to the net pen system or fish stock if given the opportunity. The initial predatory attraction to net pens might actually involve tracking prey that are seeking refuge around the aquaculture structure (Dempster *et al*. 2009b, 2010). Pinnipeds, such as seals and sea lions, represent the greatest marine mammal predatory nuisance to aquaculture operations and potential escapement through holes that they tear in the net. Even though these mammals are attracted to the marine aquaculture equipment, it is more likely that they sense excess feed or dead and moribund fish that have not been removed from the net pens for an extended period. Furthermore, access to the fish stock increases if the containment net is not properly weighted and is less taut allowing the seals to grab and tear the net mesh and possibly entering through the resulting hole. Seals within a net pen will disturb the established schooling behaviour of the fish and will begin “darting” to avoid predation. As a result, some salmon will escape through the seal access hole. Unaware site staff might also allow a hole in the mesh (which may be significant) to go unattended for an extended period of time leading to a chronic loss of the contained Atlantic salmon. Site fidelity of sharks to fish farms varies between species as some shark species will display a greater affinity while others are more transient (Papastamatiou *et al*. 2010). Affinity towards fish farms may depend on the season and activity occurring at the site with the possibility for blood to enter the water during harvest and less organized operations attracting more sharks if dead fish remain on site for extended periods. Barriers such as seal predator nets and shark guards are used throughout the industry, particularly in regions with known nuisance seal or shark populations and during times of known high predation rates, to separate the predator from the containment net. Predator nets are typically hung from the outside collar ring and have larger mesh size than the containment net, which is hung from the inside collar ring. Shark guards may be installed to protect the bottom net of the net pen based on the predatory behaviour of sharks.

Entanglement of marine mammals into aquaculture moorings and net pens has not been frequently documented and should be considered a low concern for aquaculture escapes. Most marine aquaculture sites to date have been deployed in coastal regions that large migratory mammals would likely avoid except in the case of chasing feeding opportunities. Further, unlike deployed fishing gear which is only present in the water for a soak period to allow sufficient fishing time, aquaculture operations tend to have a permanent presence and constant activity at the site may create sufficient disturbance that effectively deter marine mammals from moving within its vicinity. This might not be the case as the industry moves to more open ocean locations where daily activity will be less likely, especially during periods of foul weather, thereby removing comparable near shore disturbances.

Escapes due to vandalism may be considered another biological failure that involves humans. Fish farming frequently presents use conflicts with other established users of limited ocean space, especially as the industry moves into new areas. These conflicts may result in significant tensions if not diffused appropriately and may lead to retaliation against the aquaculture operation. Vandalism on marine fish farm infrastructure has been documented in some jurisdictions with the result being a significant escape of stock. For instance, in November 2005 an estimated 100,000 Atlantic salmon, having a stated value of $3 million, escaped from a fish farm in New Brunswick, Canada, following an event of vandalism.

BEHAVIOUR OF ATLANTIC SALMON TO ESCAPE

Hatchery Atlantic salmon are maintained in heavily stocked tanks prior to transfer to net pens. By this time, the group of fish move together with an organized schooling behaviour. These fish are transferred to the marine net pens following smoltification where the schooling behaviour breaks down for a short period as the individuals adjust to their new and larger environment. Eventually the Atlantic salmon stock will reorganize within a school that swims in a large circle determined by the size of the net pen circumference while generally avoiding the middle of the net pen volume and the perimeter close to the containment net (Juell *et al*. 1994; Oppedal *et al*. 2001). The tight schooling behaviour may disperse some at night given that no visual cues are present to see nearby fish and abrasion against the net is possible especially if the net displays bagging characteristics from strong tidal currents. Vertical distribution of Atlantic salmon in net pens is constrained by the water surface and bottom net. The fish depth position below the surface changes seasonally as light levels increase from winter to summer, perhaps to avoid elevated light levels, but moving close to the surface as feed motivation increases seasonally and throughout the day (Huse and Holm 1993; Juell *et al*. 1994). The bottom net is also generally avoided by the school perhaps as an antipredator response or to avoid physical contact as it may be elevated or flapping (Fernö *et al*. 1995).

These behavioural studies report observations that may seem counter-intuitive for many fish farm operators and observers of the aquaculture industry. For instance, many assume that stocked Atlantic salmon are actively searching for a means to escape from the net pen. To the contrary, the research indicates that small holes in the containment net that are mended in a reasonable timeframe may have little impact on chronic escape opportunities. Even diver discovery of a long tear in the containment net does not necessarily mean that a large-scale escape has occurred especially if the tear was discovered and fixed in a reasonable time after its occurrence, which could certainly be on the order of days from the time of net damage. The likelihood for escape will increase if the schooling behaviour is unexpectedly disturbed. This behaviour may occur in response to the presence of a predator inside or outside of the net pen. Escapes may also occur if the net opening is “pushed” toward the swimming school while being deformed in a strong current. However, even in this case, stocked Atlantic salmon will not simply line up and follow each other out of the net pen but rather escape in small groups. A higher risk for escape might actually occur through holes in the bottom net. During storm conditions, the fish will position themselves deeper in the water column to avoid surface turbulence. In this case, a torn bottom net could rise higher than the stocked population allowing for a large-scale acute escape to occur in a short period of time. In contrast, Atlantic cod stocked in net pens appear to be more willing to escape and sometimes chew holes in the net material and swim out through these holes (Moe *et al*. 2007).

Escape monitoring research also agree with these observations and provide insight into the motivation of Atlantic salmon to escape. Solem *et al*. (2012) reported that thirty-seven 1.4 kg farmed Atlantic salmon “escaped” after half of the containment net was lowered in the water column for 20 minutes. A more extended period was required for steelhead trout to escape after half of the containment net was lowered to a significant depth in the water column to simulate a catastrophic event leading to escape (Bridger *et al*. 2001). Both of these simulated escape events (i.e., requiring removal of half of the entire containment net) are quite dramatic and would rarely occur during normal operating conditions.

RECAPTURE OF CULTURED FISH FOLLOWING ESCAPE

The primary line of defence to eliminate risks associated with fish farm escapes always remains with the initial physical containment throughout the entire grow-out cycle until harvest. Occasionally, escape will occur from the freshwater or saltwater operations. Therefore, fish farm operators must have a mitigation plan to deal with the escapes before further ecological, financial or liability risks occur. Recapture of escapes directly by the fish farm staff, a third party contracted by the industry or regulatory agency is often cited as a potential means to mitigate the impact from escapes.

In the mid-1990s, researchers in Newfoundland and Labrador, Canada, field-tested numerous prototype recapture strategies that included candidate trap configurations and corresponding deployment periods to determine potential recapture success (Brothers 1999). Following these trials, in 1998 a method was developed to monitor the effectiveness of candidate recapture strategies using biotelemetry methods (Bridger *et al*. 2004). The telemetry system that was developed was used to successfully track the movements of implanted steelhead trout relative to the trap and leader. Though successful, the approach made no attempt to develop an optimal recapture strategy.

Knowledge of Atlantic salmon behaviour immediately following escape is essential to develop effective recapture strategies. Atlantic salmon escapes have shown considerably less fidelity to the fish farm just hours following escape (Whoriskey *et al*. 2006; Skilbrei *et al*. 2010) in stark contrast with steelhead trout that have a high percentage of escapes remaining near the farm site for at least one month following escape (Bridger *et al*. 2001). However, stomach content analysis of Atlantic salmon escapes have shown that a high number of escapes depend on excess fish feed for food. This suggests that escapes return to fish farm locations for survival some time following the initial escape behaviour (Olsen and Skilbrei 2010). Dispersion of the escaped stock also does not occur in a coherent group typical of a school of fish regardless of the size of the simulated escape event (Chittenden *et al*. 2010; Skilbrei *et al*. 2010; Skilbrei and Jørgensen 2010). Furthermore, the seasonal timing of escape does not appear to affect the affinity of the escapes to the fish farm and subsequent likelihood for possible recapture. This notion is supported by the following studies:

- Winter escaped Atlantic salmon (1.4 kg; n=37) quickly dispersed from the fish farm in no apparent pattern with few remaining 3 hours following the escape and no further fidelity towards fish farms generally observed during the study period (Solem *et al*. 2012).
- Winter, spring and summer escaped Atlantic salmon (2.8 kg, 3.0 kg and 4.3 kg respectively; n=29, 30, 30 respectively) rapidly dispersed from the escape site with mean distance away being 5-7 km after 1 day post-escape (Skilbrei *et al*. 2010).
- Summer and autumn escaped Atlantic salmon (0.16-1.56 kg; n=15-20 in each of 5 escapes) rapidly swam away from the escape site but the overall dispersion declined when comparing summer versus autumn escapes (Skilbrei 2010).

Immediately following escape, Atlantic salmon may have a tendency to dive to the bottom of the water column. This behaviour was described by Chittenden *et al*. (2010) with a study in two separate fjords having a depth of 20-40 m and 40-130 m. In another study by Skilbrei *et al*. (2009), immediate diving was observed more in autumn and winter compared with summer and often to depths of 50-80 m. After the first diving reaction, escaped Atlantic salmon prefer to remain towards the water surface with only periodic deeper dives (Skilbrei *et al*. 2009; Skilbrei and Jørgensen 2010; Solem *et al*. 2012).

Industry Codes of Containment outline various points related to recapture efforts following an escape. An example from Newfoundland and Labrador (Anonymous 2012) can be generalized as follows:

- Recapture efforts are required when losses are estimated to involve more than 100 fish and must be implemented within 24 hours of the incident.
- Gill nets or traps are allowed but must only target the escaped stock.
- Recapture must proceed for 7 days following the incident and recapture nets must be checked at least twice each day.
- Recapture activities are limited to the boundaries of an individual site that was involved in the escape incident; however, efforts beyond this area may be permitted in consultation with the regulators.
- All wild fish captured are considered by-catch to the effort and must be avoided and released alive whenever possible immediately following capture.
- Government approved training is required for all staff involved in recapture efforts.
- A recapture plan must be submitted by all farm operators and include an approved strategy that involves a set of gear per two active sites and disposal procedure for recaptured stock.

The implementation timeline, effort duration and spatial boundary for the recapture will all limit the effectiveness to recapture Atlantic salmon based on the reported escaped fish behaviour. For instance, Solem *et al*. (2012) reported that half of the tracked Atlantic salmon 12 hours following release covered an area of 17.17 km^2, while all of the tracked escapes encompassed 226.29 km^2. The required recapture effort will also need to be significantly more than 7 days and beyond the site boundary. Skilbrei and Jørgensen (2010) reported that an effort over 4 weeks and 40 km from the release site was required to recapture 37.8% and 44.6% of the Atlantic salmon that were 5.5 kg and 1.5 kg, respectively, following release in September.

The required use of gill nets at the surface is consistent with reported effectiveness of gill nets to recapture Atlantic salmon compared with surface trawls (Skilbrei and Jørgensen 2010). Skilbrei *et al*. (2010) also clearly showed that gillnetting of escapes was the most effective (77.8%) compared with bagnet (5.6%), rod from land (13.9%), or trolling (2.8%). However, surface gill nets will have little impact immediately following escape as the deep diving behaviour suggests the most effective recapture strategies hours following escape might need to focus on the entire water column in the vicinity of the fish farm. The alternative would be to wait for the escaped salmon to return to the surface following their deep dive but surface efforts will need to occur beyond the site boundary. It is worthwhile to note that recaptures reported by Skilbrei *et al*. (2010) generally occurred some distance from the site of escape and certainly greater than the site boundary.

MITIGATION OPTIONS ASSOCIATED WITH CAUSES FOR ESCAPE

The global Atlantic salmon farming industry has developed into a well-organized food production sector over the past 40 years. Many companies have taken proactive steps towards third party independent certification of their operations to meet the demands of an increasingly discerning customer base. However, the Atlantic salmon farming industry is still dealing with escapes from all stages of their operations. This paper outlined numerous causes for escape primarily resulting from structural failure of components of the net pen and mooring system, operational failure due to fish handling and farm procedures, and biological failures. Numerous reasonable practices and procedures may be implemented to achieve a goal of full containment of the entire farm stock throughout all stages of the Atlantic salmon grow-out cycle in freshwater and saltwater.

INDUSTRY LEVEL EFFORTS

1. Codes of Containment are common throughout the aquaculture industry. However, not all jurisdictions have mandatory Codes that are enacted through legislation. This should be a priority especially for jurisdictions that are presently revising existing or preparing new aquaculture specific legislation.
2. All third-party independent certification programs should include specific requirements focused on escape mitigation and reporting to remain credible.
3. The Norwegian government has implemented a mandatory standard for marine fish farm requirements that addresses site surveys, risk analyses, equipment design, engineering dimensioning, and production, installation and operation aspects to mitigate aquaculture escapes due to technical failures that has proven effective at reducing escapes within the aquaculture sector. Developing a similar standard for the Canadian/Newfoundland sector but including local fish farming knowledge is encouraged.
4. Genetic identification of escapes is possible and could be used to identify the source of escapes from specific sites. These methods do not deter escapement *per se* but should increase accountability from operators for their escaped farmed fish.
5. All operations should maintain an appropriate escape event plan that includes provisions to identify a likely escape event, a strategy to correct any deficiencies to mitigate additional losses, reporting of the escape event to the proper authorities, and appropriate follow-up steps including inventory reconciliation, analysis of the event including recent inspection reports, information sharing throughout the local industry sector, and corrective actions to equipment and practices to mitigate further escapes throughout the industry for the same reasons. Inclusion of a recapture plan might be required in some jurisdictions although these efforts appear to be futile based on present practices to recapture.

FRESHWATER OPERATIONS

New hatchery planning

1. New hatchery installations that plan to use and/or locate adjacent to surface water supplies should be aware of the risk presented for flooding that may overflow hatchery tanks, especially those located outside. Consideration of the elevation of hatchery tanks in relation to historical flood levels should be made to avoid the risk of flooding and possibility for escapement when the floodwater recedes.
2. The site survey for new hatchery construction should also consider soil type and precipitation to determine the potential for outside tanks and plumbing to become undermined, damaged or toppled in cases where flooding or heavy rainfall might weaken the surrounding soil.
3. Rearing tanks that are located outside of building structures should also be surrounded by a perimeter fence that has sufficient height and a locked gate entrance to deter trespassing and malicious activities that might result in an escape of stock.

Hatchery filtration

1. All hatcheries, including those operated by industry and governments, should be encouraged to invest appropriately to transition existing hatcheries from flow-through towards full recirculating aquaculture systems to limit the quantity of water exiting the hatchery system.
2. Filtration plumbing should always provide a diversion to a back-up system in cases when the primary mechanical filter is undergoing routine maintenance or fails.
3. Hatcheries that use settle decks and settling ponds should have these components constructed in locations and elevations that avoid seasonal flooding, which may enable escape of juveniles that have gained entry to these settling areas after floodwaters recede.

4. Additional cost-effective measures should be implemented to reduce the opportunity for juvenile fish escape including installation of effluent control measures. This may include cost-prohibitive chemical treatment of effluent to euthanize potential escapes or more cost-effective appropriately sized triple screening within the outgoing effluent pipe of all hatcheries.

   Such measures have been used to mitigate escape of exotic strains or species to local watersheds in some jurisdictions. For instance, the relevant government departments in New Brunswick, Canada requires installation of triple screens in hatcheries that are permitted to raise rainbow trout to ensure full containment of this introduced species (Anonymous 2007; Figure 13). Specifically, the New Brunswick rainbow trout policy requires that triple screens meet the following requirements:

   a) Perforated aluminium or stainless steel material is required.
   b) Hatcheries will use 18-20 gauge thickness screening.
   c) Screens must be made up of panels mounted on metal or rigid frames.
   d) Screen opening must be appropriate to contain the smallest life stage present in the hatchery (see Table 8 for specific details for oblong and circular holes).
   e) Three sets of double slot guides positioned side by side must be provided.
   f) Each screen panel must fit snugly in the guides so that spaces larger than the clear opening in the mesh do not occur.
   g) Three screens are continuously installed perpendicular to the water flow.
   h) Water level must not exceed more than half the screen height.
   i) A spare screen is required to accommodate maintenance operations.
   j) The spare screen is slipped into the spare slots while the first panel is removed for maintenance.
   k) For purpose of maintenance, screens may be removed one screen at a time for cleaning and immediately replaced.
   l) The screen shall be cleared of debris on a daily basis.

Table 8. Required horizontal oblong and round screen openings used for triple screens within the New Brunswick rainbow trout policy (Anonymous 2007).

Horizontal oblong screen slots			Round screen openings		
Fish weight (g)	Fish length (cm)	Slot size (mm)	Fish weight (g)	Fish length (cm)	Screen spacing (mm)
0.00-0.45	0.0-3.8	1.6 x 3.2	1.5	5.1	5
0.45-2.30	3.8-6.4	3.2 x 6.4	5	7.6	10
2.30-15.00	6.4-11.4	6.4 x 12.7	28	12.7	13
>15.00	>11.4	12.7 x 19.1	114	20.3	19
			284	30.5	25
			681	38.1	35

Staff training

1. Individual hatcheries should develop and implement Standard Operating Procedures (SOP’s), perhaps coupled with a Hazard Assessment Critical Control Point (HACCP) plan, related to all

aspects of the hatchery operation including use of pumps, tanks/raceways, filtration and water effluent systems to eliminate juvenile escapes from freshwater hatcheries.

2. All staff should be properly trained to operate all aspects of the hatchery to ensure that they completely understand the SOP's and HACCP plans for their specific hatchery.
3. Training of staff should also include a discussion on the importance of fully containing all hatchery origin fish to ensure that staff does not take it upon themselves to stock receiving local waterways with surplus hatchery stock.

SALTWATER OPERATIONS

General site design and deployment

1. All marine aquaculture sites should be surveyed extensively prior to deployment of any fish farm equipment. Site surveys should be completed by third parties and should include collection of complete datasets related to site currents, waves, ocean swells, wind, water depth, seabed characteristics and other oceanographic and bathymetric parameters deemed necessary for proper equipment design and deployment.
2. Collected site survey data should be available to complete professionally engineered site plans (i.e., moorings, surface collars, nets) with regards to design and dimensions based on site specific environmental conditions using established engineering methods.
3. Specific component design should also consider fatigue, concentration of stress loads, and corrosion in the anticipated site environment to avoid premature structural failure and escapes.
4. Wherever possible, the net pen and mooring system design should include redundancy of critical components and sufficient safety factors to minimize total system failure and escape.
5. Professional engineers should be actively engaged to provide engineer stamped site plans that meet the operator production targets and site environmental conditions. The site operator should deploy the equipment according to the plan at all times and the site inspected following installation and audited periodically without notice.
6. All sites should be appropriately marked to avoid collisions from vessel traffic that may also frequent the area.

Surface collars

7. Bridles and collars should be appropriately marked so that the connections are spread equally within the surface collar across all bridles to limit the opportunity for kinking and structural damage of the collar.
8. Damaged or sinking surface collars should be attended to immediately to stabilize the situation and ensure the containment net is not breached or the net pen does not sink.
9. Deployment of net pens in higher energy environments should include a surface collar configuration that provides the required strength and transparency to incoming waves. These collars should not be designed to ride high on the surface, but rather have adequate buoyancy to float while allow passing waves to travel through and over the collar. These principles have been implemented in the shipping industry for decades where ballast is used to weigh ships down for ocean voyages so that the centre of gravity is lowered and stability increased during heavy seas. In the case of HDPE collars in higher energy, the goal should be to increase strength to withstand increased environmental loads while not increasing buoyancy that will result in greater exposure to incoming storm energy. This can be achieved by:

   - Using smaller diameter HDPE pipe that has increased wall thickness to increase its strength while decreasing the surface profile and subsequently the forces experienced.
   - Deploying three surface pipes within the collar to give the required strength and buoyancy but spread over three rather than two surface pipes thereby reducing the individual pipe profile that is exposed to incoming storm energy.

- Increasing the weight ring mass so that a larger strong surface collar rides lower at the surface to increase its transparency to passing waves.
- Net pens that are able to submerge should be explored to avoid severe storm conditions that may damage net pen components and result in escape (example described by Bridger and Dobson (2010)). Submersion of Atlantic salmon in net pens for the time required to avoid damaging surface perils have been studied with no lasting deleterious effects noted (Dempster *et al*. 2009a).
- Net pen configurations that are not connected to the surface collar should be explored for higher energy sites, such as those described by Colbourne and Allen (2001) and Bridger and Dobson (2010), to avoid damage to the fish farm infrastructure.

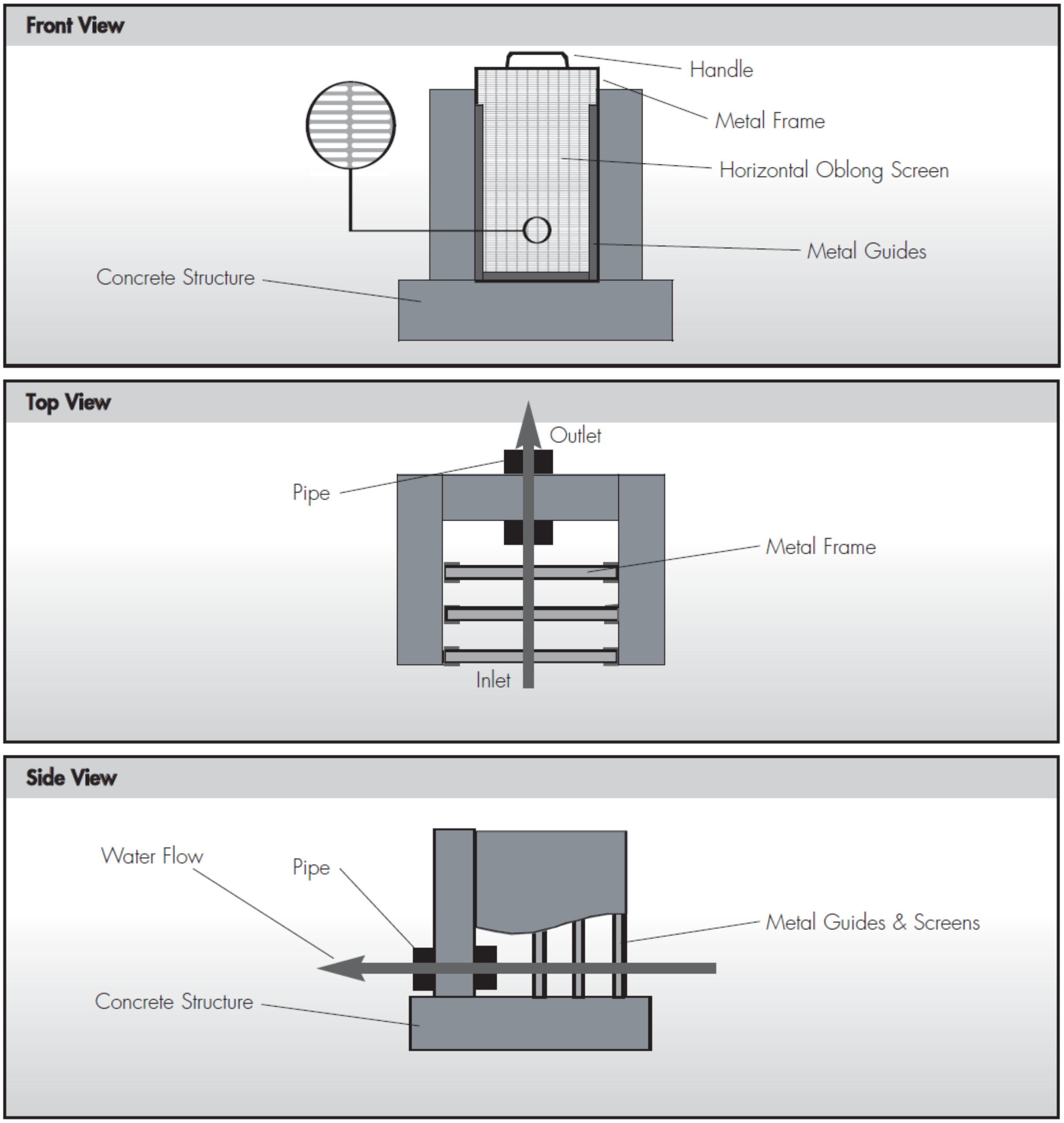

Figure 13. Visual representation of the permitted triple screen design to allow culture of rainbow trout in commercial hatcheries in New Brunswick, Canada.

Nets

10. All net material should meet or exceed the required breaking strength for the specific oceanographic conditions anticipated for the site. As an example, jurisdictions across Canada frequently cite the British Columbia aquaculture regulatory requirements regarding net strength. In this scheme, net pens are provided with a dimension classification on the basis of its perimeter and depth followed by a minimum breaking strength associated with each size category and specific mesh size (Table 9). While this approach correctly implies that larger net pens will have greater forces applied to the containment net, it is limited when considering that different sites will experience a range of environmental loads. However, these values provide a reasonable baseline for further refinement.

Table 9. Minimum required breaking strength for increasing net pen size on the basis of surface collar perimeter and containment net depth.

	Minimum required mesh breaking strength for each dimension classification (kg)				
Mesh Size	A	B	C	D	E
<22mm (⅞”)	20	25			
>22mm (⅞”)-<38mm (1½”)	26	31			
<38mm (1½”)			36	41	46
38mm (1½”)	31	41	46	51	62
>38mm (1½”)	41	46	51	62	77

11. Breaking strength values presented in Table 9 should be expanded to include provision for site specific environmental conditions along with the net sizes based on net perimeter and depth.
12. Nets should be tested for break strength prior to and throughout deployment using established practices and on a schedule that reflects the age of the net and the conditions of the specific site.
13. The containment net mesh should always be sized appropriately to retain the smallest stocked fish whenever smolt are entered or following net changes. Mesh sizes should be chosen such that the stretched mesh dimension is less than one-third of the size of the widest part of the smallest fish body as determined by Rideout and Saunders (2001) to prevent fish escape (Table 10).

Table 10. Maximum mesh size required to retain cultured Atlantic salmon on the basis of fish weight.

Maximum inside mesh size (inches)	Minimum Atlantic salmon weight (g)
1 ⅛	50
1 ⅜	84
1 ⅝	117
1 ¾	134
2	167
2 ¼	500

14. The industry should consider a shift towards eliminating net changes, only using a single net for the entire grow-out cycle that has a mesh size small enough to contain the smolt entered on the site. Frequent net cleaning while deployed should be implemented as a standard farm task to

keep the smaller net mesh clean at all times to reduce total system loads from passing waves and current.

15. The top bird net should have a mesh size that matches or is less than the containment net at all times to ensure that no fish will escape if the net pen is accidently or intentionally submerged for any reason.
16. The top bird net should be maintained at all times when the site is left unattended. The top net should also be secured to the containment net along the entire perimeter to provide additional protection to and confinement of the fish stock.
17. Containment nets should be installed such that all of the weight of the net and biofouling is buoyed by the surface collar float pipes and not the handrail to prevent unnecessary damage (i.e., the jump net should always retain sufficient slack to indicate that none of the weight is placed on the collar handrail).
18. All containment and predator nets should be properly weighted to reduce the effect of current on net deformation and associated stress and to deter successful predatory attacks.
19. The contained stock should always be maintained within a double layer of net to provide necessary redundancy at all times throughout the grow-out cycle. A double layer may be facilitated at the time of entry by integrating an internal nursery net, perhaps by using the bird net stand as the nursery net collar as described by Bridger and Dobson (2013). Alternatively, the double layer may be provided by deploying a predator net having the same mesh size as the containment net.
20. An exterior net should always be installed even in areas with no known predators to protect the containment net from large debris that passes through aquaculture sites periodically without notice and may tear significant holes in the net, facilitating escape.
21. All installations of two nets should maximize the distance between the net layers to provide greater protection from predatory attacks (i.e., the containment net is hung from the inside of the surface collar while the second net is secured to the outside of the surface collar).
22. Propeller guards should be used throughout the entire vessel fleet to eliminate the possibility of entanglement with and damage to the containment net.
23. Some companies are moving away from use of anti-foulants and this process should be encouraged for reasons not related to escape prevention. However, even in these cases all nets should receive acceptable UV protection to ensure that the net structural integrity does not rapidly deteriorate while deployed.
24. New net developments have occurred in recent years and the industry, with assistance from government programs, should explore and monitor use of these novel approaches including co-funding. Examples of new nets that might prove beneficial include copper alloy material that is expected to provide additional strength while eliminating biofouling.
25. Proper selection of material for the mesh and integrated ropes should be made to ensure that the net performs as it should particularly in higher energy conditions with the ropes taking the loads and not the net material.

Moorings

26. All mooring components should be designed and dimensioned by professional engineers to withstand anticipated site conditions including an acceptable safety multiplier.
27. All shackle pins should be completely tightened with a wrench and secured with two cable ties to provide back-up redundancy.
28. An appropriate maintenance and replacement schedule should be developed in conjunction with the site engineer and adhered to by the operator as part of an effective preventative maintenance strategy.
29. All mooring bridles should be regularly checked for damage from propellers, abrasion, etc. to ensure that there is no risk that a bridle may break thereby placing the entire drag force to hold the net pen on a single bridle.

30. No additional farm infrastructure (e.g., feed barges) should be moored within the approved net pen submerged grid system without prior consent and planning provided by the design engineer to ensure that the additional loads remain within the design parameters.

Fish handling

31. Regular inspections of all fish transfer equipment should be completed before, during and after the transfer operation is completed. Any deficiencies observed should be remedied immediately and noted within an appropriate corrective action report for later analysis.
32. All transfer hoses and couplings should be double walled or wrapped with an appropriately sized mesh net to provide redundancy. Further redundancy should be provided by securing a drop safety net of appropriate mesh size that covers the entire work area below the transfer hose to prevent escape in cases of sudden and unexpected failure during transfer associated with smolt entry, fish health treatments, harvesting and other fish transfer operations.
33. Special care should be taken when harvesting with Braille nets such that harvested fish cannot easily escape by jumping out of the net during transfer. Appropriate placement of drop safety nets under the work area should minimize this opportunity for escape.
34. Multiple stocking strategies of net pens should be avoided at all times.
35. In the unfortunate case that multiple stocking is necessary, stock splitting should never be completed using swim through operations given the elevated opportunity for escape and difficulty in achieving reasonably accurate counts for inventory control compared with transferring stock in a hose and splitting using a grading table.
36. Special care should be taken while sampling fish, as escapes from dip nets may occur without notice. Dip nets should also be inspected for holes prior to use. The fish sampling procedure should also be completed with use of a drop net covering the entire work area or in an enclosed area rather than on the net pen surface collar to reduce the risk for escape.
37. Any fish transfer operation with an observed escape should be stopped immediately and the specific cause of escape rectified prior to restarting the operation.

Farm procedures

38. Net changes should be avoided as much as possible and the industry should be encouraged to integrate regular net cleaning operations while the containment net is deployed. This strategy should provide the added benefit of eliminating the use of anti-foulant treatments on nets.
39. If net changes are required, the new net mesh size should contain the smallest fish size and not just the average fish size.
40. All jump nets should be secured after divers have entered each net pen to mitigate possible escapes while jump nets are otherwise lowered to facilitate diver entry.
41. Net pen towing while stocked should be avoided as much as possible. However, in some cases these operations are required as a normal part of the business and the operation should be well-planned, nets should be inspected by divers before and after the tow, towing should be completed with vessel redundancy nearby, and the operation should be monitored at all times to ensure connections are appropriate and entanglement in any debris is avoided.
42. Divers should be involved in farm inspections whenever a possible escape is expected or fish stock swimming or feeding behavior is observed to be sufficiently unusual for an adequate period of time (i.e., 48-72 hours).
43. All excess feed remaining on site should be appropriately stored (i.e., inside buildings or covered with tarps) such that its presence will not attract unwanted predators to the operation that may cause escapes. Overfeeding should also be avoided to minimize feed accumulation on the bottom net, especially if fouled, and serve as a possible predator attractant.
44. All harvest waste including blood water should be contained on the vessel to avoid attracting predators to the site that might cause a general nuisance and damage to the net pen resulting in possible escape.

45. Designated docking areas should be identified for each net pen that will allow the greatest opportunity to approach without causing any unwanted damage. Large vessels should be tied to the surface collar float pipes and no vessels should be tied to the net pens in poor weather conditions.
46. Appropriate vessel docking procedures should be developed and adhered for all vessel sizes that frequently visit the net pens to complete various tasks. Large vessels should only approach net pens with the assistance of visual contact by a second individual.

Inspection and maintenance

50. All farm equipment should be thoroughly inspected following installation but prior to fish entry to ensure that the deployment meets the approved engineered plan.
51. Containment nets should be inspected by divers weekly during use for holes, broken or damaged ropes, and signs of chafing. All deficiencies should be corrected immediately if they are observed by divers during use. Divers should also relay information related to the degree of biofouling on nets so that cleaning or changes are completed as necessary in a timely fashion.
52. All farm equipment should be thoroughly inspected twice annually – in the spring and autumn – with the use of divers and remotely operated vehicles to prepare for the stormy winter season and correct deficiencies following winter. These inspections should be recorded and the video files maintained for an adequate period of time following the inspection.
53. Thorough containment net inspections should occur following every significant storm event experienced at the site and issues corrected before escapes occur.
54. Daily site crews should be appropriately trained to recognize issues apparent from the surface and encouraged to report these to the proper management officer to mitigate chronic or acute escape. Such visible cues might include a change in the feed intake that could indicate a loss of fish or improper alignment of compensator buoys that might suggest slippage of specific anchor lines.
55. All components repaired while deployed should receive additional inspections until the component can be replaced.
56. Operators should consider integration of an automatic dead fish collection system to facilitate daily mort collection from all cages. This strategy should help to eliminate predator attraction and also remove this task from the weekly site dive thereby giving more time for divers to inspect and correct net deficiencies.
57. All companies should implement an appropriate inspection response strategy to ensure that appropriate actions are taken to correct any issues observed. Inspection sheets should also include a place for involved individuals to sign the sheets to increase accountability within the site crew.
58. All debris in the vicinity of or observed floating towards the site should be removed immediately and appropriately disposed of to prevent direct interaction with the net pen systems.
59. Ice tarps should be installed seasonally as necessary to proactively protect the net pens from freezing spray and any resulting damage or accidental sinking to the net pen giving potential for fish escape.
60. Sites located in known areas that may experience seasonal ice flows should develop and implement an ice contingency plan that may include deployment of ice booms, breaking and redirecting ice flows, or periodic short-term net pen submersion to avoid ice flows.

Record keeping

61. All equipment deficiencies and repairs should be properly logged for internal analysis and external audits as necessary.
62. All components of each net pen should be tagged with an individual identification code that may be easily viewed and retrieved. The entire history for each individual component should be maintained within a company database so that use, inspections and maintenance records are

readily available as required and retirement of specific items is possible when the anticipated life expectancy is reached.

63. An audit process should be implemented throughout the farming industry that involves third-party independent review of the equipment deployed compared with the approved professionally engineered site plan.
64. Stock numbers per net pen should be updated immediately following mort removal. Monthly inventory reports should be maintained by the site and company managers at all times to allow quick reconciliation and escape reporting as necessary.

Staff training

65. All companies should develop and implement Standard Operating Procedures (SOP's), perhaps coupled with Hazard Assessment Critical Control Point (HACCP) plans, related to all aspects of the marine fish farm equipment and operations.
66. All staff should be properly trained to operate all aspects of the marine fish farm, including proper use of all equipment and vessels while around and attached to farm equipment and basic knot tying knowledge, to ensure that they completely understand the SOP's and HACCP plans for their employment.
67. Training of staff is imperative before new net pen systems and strategies are integrated within an existing operation. Experiential learning is highly desirable whenever possible by sending staff to embed with other sites or operators that are already using the new technology.
68. Supplier companies should employ an accredited workforce as necessary to ensure that welding and net manufacturing services meet the highest standards achievable.
69. Site feeding staff should be trained to recognize feed rate issues that might indicate an escape of stock and be aware of the proper line of communication to report such observations in a timely manner.

Recapture

70. The priority for farm crews should always be to secure the site and any remaining stocked fish even after an escape event has been identified.
71. Recapture efforts as presently practiced are not sufficiently successful to warrant continuation. However, research in this area might improve the rate of recapture if escaped fish were trained to return to a recapture area based on behavioural conditioning. Sutterlin *et al*. (1982) demonstrated that Atlantic salmon imprinted to a synthetic chemical cue for 21 days at the hatchery prior to release appeared to imprint to return to the same cue at a later age. Acoustic conditioning has also been demonstrated in Atlantic salmon with 85% of the exposed salmon conditioned after 7 days of exposure to the acoustic cue and the conditioning was retained for at least seven months (Tlusty *et al*. 2008). Both of these studies suggest that imprinting during or directly after the smoltification process may be possible and could subsequently be used as part of an effective recapture strategy. Further research is warranted in this respect.

CONCLUSIONS AND RECOMMENDATIONS

The primary purpose of this paper was to review aspects of physical containment of Atlantic salmon throughout the aquaculture grow-out cycle, with respect to escape opportunities and mitigation. More specifically, this report was requested by Fisheries and Oceans Canada as part of a Canadian Science Advisory Secretariat (CSAS) process related to the potential effects surrounding the importation of European-origin cultured Atlantic salmon to Atlantic salmon populations and habitats in Newfoundland and Labrador, Canada.

The approach throughout this paper was to review generic equipment and practices frequently used in the global Atlantic salmon farming industry given relatively standard practices, procedures and, sometimes, regulations generally apply to the Atlantic salmon aquaculture sector regardless of geographic location.

The majority of farm escapes occur from marine containment systems and broad causes for marine Atlantic salmon escapes are categorized as structural failures of the net pen and mooring system components, operational failures related to fish handling and farm management practices, and biological failures primarily associated with predatory attacks. A detailed list of possible mitigation options has been presented. Evaluating and prioritizing specific mitigation measures based on effectiveness to prevent escape is highly problematic given the lack of data regarding cause-and-effect, linking a specific measure to absolute reductions in escape. As the aquaculture farm system is an integrated unit comprised of numerous integrated components, even the smallest item installed or operated incorrectly may have a dramatic effect on the possibility for an escape occurrence. Further, the effect of each mitigation measure in reducing risk to the receiving ecosystem may be influenced by the seasonal time of escape, age of the fish at time of escape, and scale of the escape. Intuitively, large escape events may seem to pose a greater risk so every effort should be made to prevent high numbers of Atlantic salmon from escaping in any given event. However, recent modeling efforts, as presented during this CSAS process (Baskett *et al.* 2013a, b; Verspoor *et al.* 2015) imply that small-scale low frequency escapes represent an equal risk from an impact perspective and, therefore, must also require mitigation.

The detailed list of possible mitigation measures are presented in this report, however, these specific items may be more broadly presented as the following high level recommendations:

- Codes of Containment should become mandatory within jurisdictional legislation and a condition of the appropriate approval to operate or aquaculture license. Furthermore, regulatory departments should consider developing an industry standard similar to the Norwegian standard for marine fish farms given the compelling evidence that implementation of the Norwegian standard has resulted in a dramatic decrease in total fish farm escapes throughout its aquaculture sector.
- All existing and potential freshwater and saltwater Atlantic salmon aquaculture sites should be extensively surveyed to collect pertinent information that may contribute to escapes from the operations. Freshwater site surveys should include items such as soil type and floodwater data. Marine sites should be monitored for oceanographic, vessel traffic and seabed characteristics.
- Selection of appropriate equipment should involve a professional engineer to properly design and dimension all components prior to installation of Atlantic salmon fish farms. Deployed equipment should be regularly audited for compliance with the engineered design to ensure proper maintenance continues during use.
- All equipment and operations implemented should include aspects of redundancy, fail-safe design and safety margins for the specific environment to increase the likelihood for full containment of the Atlantic salmon stock throughout the grow-out cycle.
- All operators should ensure that its entire staff is properly trained and understand all standard operating procedures to operate all required equipment and facilitate all necessary fish handling and farm operations to mitigate fish farm escapes.
- Finally, the Atlantic salmon industry generally remains an innovative sector and this attitude should continue with regards to escape mitigation and might include aspects associated with new equipment (e.g., net pen design, new net materials) and handling procedures.

Recent evidence from Norway clearly illustrates the possibility that escapement from aquaculture operations can be mitigated when the industry is managed using an appropriate set of methods, potentially through regulation. In Norway, this manifests itself in the form of a far-reaching standard that outlines the equipment requirements for use in specific environmental conditions and increases accountability through the use of molecular methods to identify escapes to specific farms.

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