Risk of intrusion of farmed Atlantic salmon into Icelandic salmon rivers

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Errata November 2023
Information about two salmon in River Fífustaðadalá (see table 3.2) was published by mistake on the website of the IMFR on the 21st December 2018. The samples were property of Laxfiskar ehf (Jóhannes Sturlaugsson, pers. com.). The institute regrets this mistake.

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1. Introduction

Marine farming of Atlantic salmon (*Salmo salar*) is a big industry in the North Atlantic. The production of farmed salmon in the North Atlantic countries grew from 200 thousand tonnes in 1992 to about 1.4 million tonnes in 2012 but has been relatively stable since. Norway is by far the biggest producer with a production of 1.1 million tonnes in the year 2018. The reported production from other North Atlantic countries for 2018 was; 138 thousand tonnes from Scotland (UK), 65 thousand tonnes from the Faroe Islands, 18 thousand tonnes from Canada, 14 thousand tonnes from Russia, 13 thousand tonnes from Ireland and 13 thousand tonnes from Iceland (FAO Fishstat numbers). The recent stagnation in the production of the main production countries Norway and UK, can be explained by the lack of available farming locations, sea lice problems, and concerns with introgression of farmed fish into wild stocks, bearing in mind that Atlantic salmon is native to the North Atlantic and is divided into populations, unique for each river (Gilbey et al. 2018).

Farmed Atlantic salmon differs genetically from wild salmon, as breeding programs change the genetic make-up (Glover et al. 2017) of farmed Atlantic salmon towards improvements of commercially important traits, such as growth, feed utilization, and fillet quality. Breeding programs for farmed Atlantic salmon were first established in Norway in the early 1970s based on salmon collected from several populations in central Norway.

Because of reduced fitness and lower genetic variation in farmed salmon, compared with their wild conspecifics, there is a concern that escaped farmed salmon might reduce the viability of wild salmon populations through genetic introgression (Baskett et al. 2013, Huisman et al. 2012).

Using collectively informative SNP markers developed by Karlsson et al. (2011), a reference panel of Norwegian farmed salmon, historical and contemporary samples from 20 wild salmon populations distributed throughout Norway, and approximate Bayesian computation-based estimates, the first estimation of cumulative gene flow from farmed salmon to wild salmon was produced (Glover et al., 2013). These authors estimated that over the period of the study (three to four decades), introgression of farmed salmon ranged from 0% to 47% per population, with a median of 9.1% with a range of mean level og introgression between 0.0% and 42.2%.

Genetic introgression from farmed salmon was quantified in salmon populations in 147 rivers in Norway, using the SMP markers. In 109 rivers with adult contemporary samples (Karlsson et al. 2016) and sample sizes of 20 or more, the average level of farmed genetic introgression were 6.4% (mean 6.4%, median 2.3%). Fifty-one of these rivers showed significant genetic introgression of farmed fish when compared with historical reference samples.

Salmon escapees from farming compete with wild fish for food, space and breeding partners. As a result of morphological, physiological, ecological, and behavioural changes that occur in hatcheries, their competitive ability often differs from that of wild fish. These changes are both phenotypic and genetic. A problem, therefore, arises when farmed salmons escape from their pens as they may breed with wild salmons and cause a genetic influx of less desirable genes into the wild population.

1.1 Salmon stocks in the North Atlantic

When assessing the status of the Icelandic salmon stock, it is useful to compare it with the condition of other salmon stocks in the North Atlantic. In the years around 1970, the total registered global catch of Atlantic salmon was often in the range of 11-12 thousand tonnes per year which corresponds to approximately 3-4 million salmon. The leading nations in salmon fishing were Greenland and Canada with 2000-2500 each nation followed by Norway, Ireland and Scotland, 1500-2000 each, Russia and England approximately 600 and Icelanders with approximately 200 tonnes. The total catch (including unlisted catch) remained in the range of 7-11 thousand tonnes in the 1980s but has since then declined steadily. In the year 2000, landings were down to approximately 4000 tonnes, of which Norway caught 1200 and Ireland 700 tonnes. In the years 2010-2014, the average total catch was down to just under 1800 tonnes (including unlisted catch). Of these, Norway had 600, Canada, Scotland, Iceland and England with 110-143 and Ireland and Russia with 84 tonnes each nation (Working Group on North Atlantic Salmon, 2015).

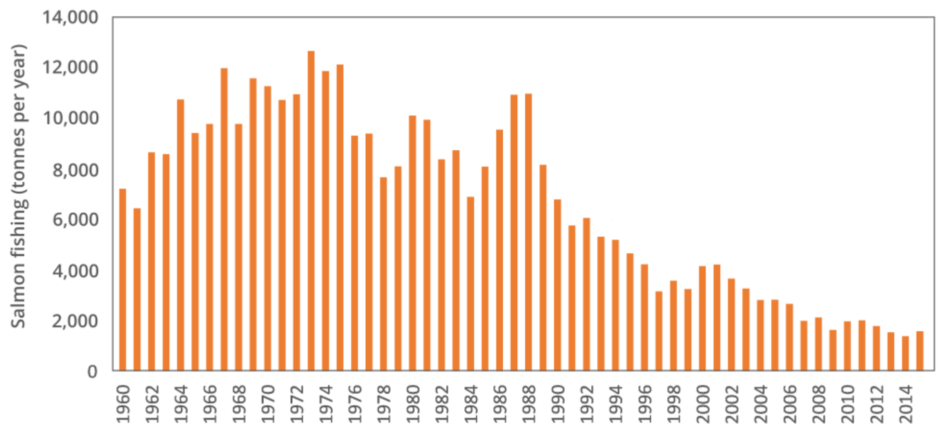


Figure 1.1 Total catch of Atlantic salmon caught during the period 1960-2015. The chart shows the reported total catch of all fishing nations plus the estimated unlisted catch since 1986 (Working Group on North Atlantic Salmon, 2015).

At present, total Atlantic salmon fishing is only about 1/6 of what it was thirty years ago and is now just over half a million salmon per year (Fig. 1.1). Fishing for salmon is now almost entirely a by-catch, except in Norway, Russia and the British Isles where considerable net fishing is still being carried out and the coastal fishing amounts to about one-third of the total catch (Working Group on North Atlantic Salmon , 2015).

The high reduction in the total catch of Atlantic salmon reflects the corresponding reduction in stock size. It is generally believed that a part of this decline of the stock can be traced to various human activities, e.g. over-fishing, global warming, pollution, power generation and aquaculture (Working Group on North Atlantic Salmon, 2015). Overfishing is by far the most important reason and the stock may still be recovering from the overfishing of salmon that took place on the feeding grounds of western Greenland in the years 1950-1980. These fish came from the rivers of Europe and America and for the most part, they were large salmon that had spent two winters in the sea (2WS). Overfishing of the large salmon has probably led to less recruitment and weaker salmon stocks. The impact was evident in Icelandic rivers as the large salmon ratio is now only 10-15% but was around 50% at the beginning of the 1970s (Gudbergsson, 2016). The net fishing by Icelanders on large salmon in the sea and rivers has reduced the number of large salmon but not small salmon. Generally, the status of Icelandic salmon stocks is good, whereas most other salmon stocks have declined (Working Group on North Atlantic Salmon, 2015).

1.2 Salmon angling in Iceland

Catches from angling in Icelandic salmon rivers have been relatively stable since accurate logging started (Fig. 1.2). The fishing effort has not changed during the past four decades and number of caught fish are generally regarded as a good relative measure of the size of Icelandic salmon stocks (Jónsson et al., 2008). The fishery is divided into four main categories and corrected for catch/release fishing (30% recovery estimated) (Gudbergsson and Einarsson, 2004, 2007).

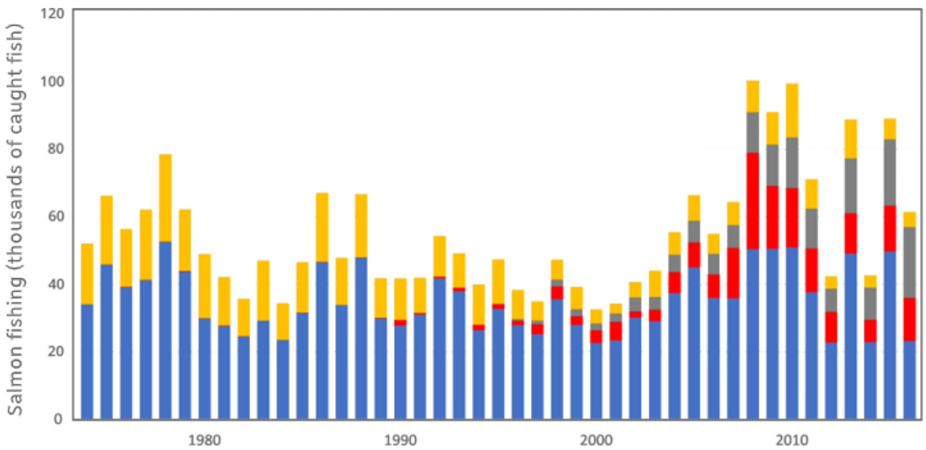


Figure 1.2 Overview of salmon fishing in Iceland during the period 1974-2016. The fishery is divided into four categories according to the fishing and ranching method. Yellow is net fishing, grey is catch and release, red is angling of ocean ranched salmon and blue is angling of wild salmon. Values for 2016 are partly based on estimates (Gudbergsson, 2016).

The gill net fishing (Fig. 1.2 yellow pillars) was, in the first half of the period, often close to 20 thousand salmons a year. Since 1997, net fishing has only been practised in freshwater (rivers) and the numbers have usually ranged between 4-10 thousand salmon. The highest numbers are caught in Thjórsá (50-60%) and Hvítá / Ölfusá (40-50%).

The sea ranched salmon (Fig. 1.2 red) begin to enter into the fishing around the turn of the century and since 2007 ranching has given an average of 15 thousand salmon per year. Approximately 95% of the catch comes from Ytri- and Eystri-Rangá, while other rivers where sea ranching is practised are Breiddalsá, Tungufljót, Skógá and Nordlingafljót. Sea ranching rivers are commonly not catch and release rivers. The practise of catch and release (Fig. 1.2 grey) started the scene at the turn of the century. In recent years, approximately 35% of angled wild salmon are released back alive into the rivers. The catch rate of one-sea-winter (1SW) small fish has remained fairly stable since 1974 (50%), while the catch rate of multi-sea-winter (MSW) salmon has declined significantly in recent years (from 70% to 50%) (ICES 2019).

The number of killed fish (Fig. 1.2. blue) has fluctuated between 22-50 thousand throughout the period. Interestingly, the catch has been historically high for the past ten years, except for the years 2012 and 2014. With the advent of ranching and catch/release, along with a reduction in gill-net fishing, there has been a substantial increase in the total number of angled salmon (up to 80-90 thousand salmon in the best years). A total of 76 salmon rivers in Iceland have yielded an average catch of over 60 salmon per year during the period 1974-2015 and 64 Icelandic rivers have yielded on average over 100 salmon per year (Gudbergsson, 2016). The rivers with the highest catches of salmon in 2016 were Ytri-Rangá (9323), Midfjardará (4338), Eystri-Rangá (3254) and Blanda (2386). Other good fishing rivers with over 1000 salmon catches are Thverá / Kjarrá, Laxá í Dölum, Langá, Haffjardará, Nordurá, Laxá í Adaldal, Haukadalsá and Vídidalsá. Vatnsdalsá, Selá í Vopnafjördur, Hítará and Ellidaá have a slightly lower yield.

It can, therefore, be assumed that the Icelandic salmon rivers can, with ranching and reduced gill-net fishing, sustain fishing of about 70 thousand salmon per year. In context with salmon farming, it can be estimated that the total salmon catch in Iceland amounts to about 175 tonnes per year (based on an average of 2.5 kg), which corresponds to approximately 1/60 of the production of farmed salmon in Iceland 2017. The direct value of fishing permits in Icelandic salmon rivers and total value creation with secondary indirect effects (accommodation, catering etc.) is estimated as 20-30 and 10-14 million euros per year, respectively (Steinsson, 2010). This indicates that each caught Icelandic wild salmon creates value that amounts to approximately 1,800 euros.

1.3 Status of the Icelandic salmon stocks

Large salmon is defined here as a salmon that has been two or more winters in the sea before returning to rivers to spawn. In catch reports, large males are classified as > 4 kg and large females >3.5 kg, while fish below this size limit is classified as small. Genetic studies have shown that the salmon has a certain gene that determines the time at sea (Barson et al., 2015).

The proportion of large salmon caught in Icelandic rivers was approximately 50% in the first ten years after data registration began, but from 1985 the proportion dropped to 10% in the year 2000. The main reason for this is considered to be higher mortality rates for salmon during the second year at sea. After the practice of catch-and-release of large fish was adopted in Iceland, the proportion of large salmon in the catch has been growing again and was up to 14% in 2015 (Gudbergsson, 2016).

Measurements have also shown that the average weight of caught salmon has steadily declined since measurements began in the 1970s when the average weight of large and small salmon was approximately 6 and 3 kg, respectively. The average weight of large salmon fell to 4.5 kg in 2006-2009 but rose again to 5.1 kg in 2015. The average weight of small salmon fell to 2.1 kg in 2013 but increased again to 2.3 kg in 2015. This trend indicates that the large salmon is recovering (Gudbergsson, 2016; Einarsson and Gudmundsdottir, 2017), but it may also reflect variable food availability in the sea.

Looking solely at the number of landed natural salmon (Fig. 1.2, blue and yellow), the catch number during the last 12 years is generally very similar to that in the sixties and seventies. This can, however, give a misleading picture of the development, because the composition of the catch has changed significantly during the period. The proportion of large salmon has fallen sharply, and the landed biomass has therefore decreased substantially (Fig. 1.3).

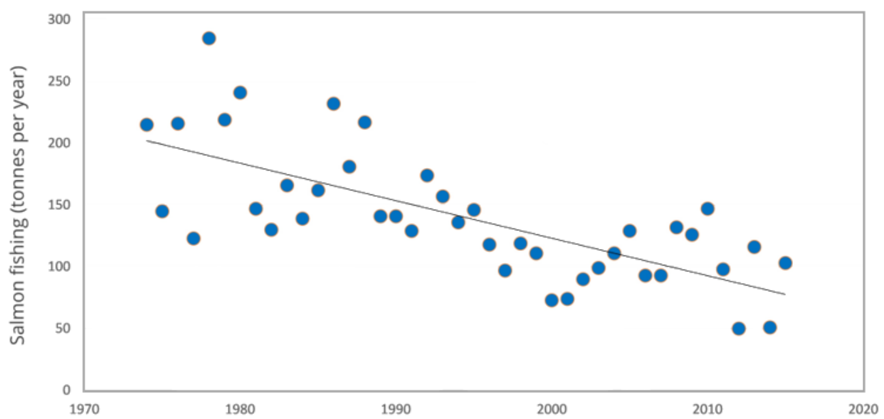


Figure 1.3 Overview of the registered catch of natural salmon in Iceland during the period 1974- 2015. This is the total weight of salmon from angling and net fishing (ICES 2016).

Due to the falling average weight in the catch (from 4-5 kg to 2-3 kg), landed catch has dropped from approximately 200 tonnes down to 100 tonnes per year in the most recent years. The catch-and-release of live fish has some effect, especially in the last three years, but does not change the results significantly. The total catch has remained around 100 tonnes since 1995 (Fig. 1.2), and most likely the catch will not recover to the previous levels unless the number of large salmon increases significantly. The sustainable total fishing (angling and net fishing) from the natural Icelandic salmon stock is of the order of 50 thousand salmon per year (Fig. 1.1). In the years before 1985, this catch would normally have been divided into 25 thousand small and 25 thousand large salmon. Today, however, the division of the catch is closer to 42 thousand small and 8 thousand large salmon. Therefore, the total number of small salmon has increased significantly at the same time as the number of large salmon has decreased (Gudbergsson, 2016).

For some time, it was thought that Icelandic salmon was a by-catch of pelagic vessels and the main reason for the reduction of large salmon in Icelandic rivers (Gudbergsson and Sigthorsson, 2007). Genetic research has, however, revealed that salmon obtained as by-catch in the mackerel fishery in Icelandic waters is only to a small extent of Icelandic origin but originates mostly from continental Europe, Scandinavia and Russia (Olafsson et al., 2014).

Icelandic salmon are thought to migrate mainly to the waters of Greenland, where a similar decrease in the occurrence of large salmon has occurred (Isaksson et al., 2002). Fishing for large salmon in Greenlandic jurisdiction has been increasing in recent years, and Canadians are particularly concerned about this. The fishing of large salmon in the Atlantic Ocean is much greater than the recommendations of ICES and NASCO and works against the goals of stock enhancement (Working Group on North Atlantic Salmon, 2015). Similarly, it could be an important issue for Icelandic anglers if fishing for salmon would be reduced in this area.

1.4 Genetic structure of Icelandic salmon stocks

Research has revealed genetic variation between Icelandic salmon stocks and has shown that each river has its own specific strain. Icelandic salmon is remotely different from other Atlantic salmon stocks. Largest genetic difference is between American and European salmon. For European salmon, a hierarchy of regional genetic assignment units have been defined using a combination of distance-based and Bayesian clustering. At the top level, three assignment units were identified comprising northern, southern, and Icelandic regions (Gilbey et al., 2018). This indicates that Icelandic salmon forms a special genetic group that differs from the remaining European salmon. The Norwegian salmon is therefore genetically distant from Icelandic salmon.

Two major genetic studies have been performed on the stock populations of Icelandic salmon. The first study was carried out in the years 1990-1994 and focused on the salmon stocks of 32 rivers and three breeding farms with native salmon. The study revealed that each river had a distinct strain and 6.2% of the genetic variations could be explained by difference between stocks. Other genetic variations could be explained as variability within strains (Daníelsdóttir et al., 1997). In the second study, carried out in 2008-2011, the genetic variation of salmon stocks was assessed in 26 Icelandic salmon rivers using 15 microsatellite loci (Olafsson et al., 2014, 2010). The project was part of the European research project Salsea / Merge, where salmon in its entire distribution area was studied with respect to genetic and ecological issues in the sea (Fig. 1.4).

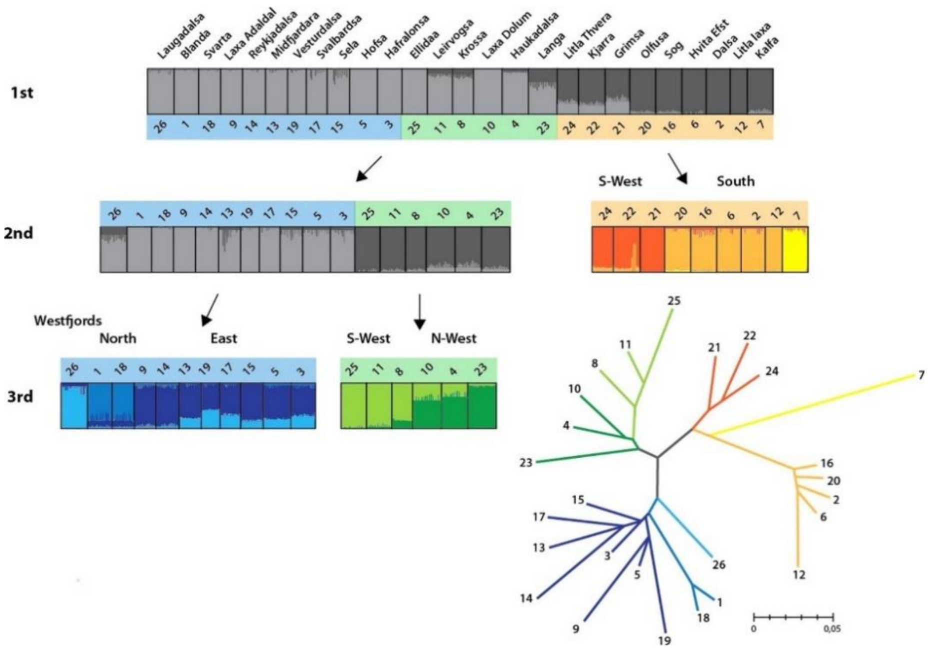


Figure 1.4 Population structure as estimated from three levels of hierarchical STRUCTURE analysis. (Olafsson et al., 2014)

The information on the genetic structure resulting from these projects opens the possibility of tracing fish to rivers as well as finding any hybridization.

1.5 Salmon farming in Iceland

Stock enhancement in rivers and lakes has been practised since 1883 in Iceland. Experiments with sea ranching of Icelandic salmon were started in 1963 at the official breeding station in Kollafjördur. At the end of the 1980s, there was a substantial increase in sea ranching, but due to poor recovery, operations halted before the turn of the century. As of now, sea ranching is only used to enhance the stock in rivers using broodfish from that particular river (Gunnarsson, 2002, 2007). Trials with salmon farming in sea cages began in 1972, and on-land salmon farming began in 1979. The cage farming proved difficult to operate and on-land farming took over in the 1990s, but production never exceeded two thousand tonnes a year.

Around the year 2000, interest in cage farming reappeared and production in cages increased to around 6 thousand tonnes in 2004-2006. Due to operational problems and low product price at that time the operations stopped in 2007. Production was low the following years until Fjardalax started its operation in 2010 and salmon farming in net-pens started to take off.

The production ranged between 3 - 4 thousand tonnes for several years, but in 2016 there was a turning point when production more than doubled in one year. The production has increased rapidly during the recent years, to 11.7 thousand tonnes in 2018 and 26.9 thousand tons in 2019 whereof 25.3 in net pens. Today, licenses have been issued for farming of about 30,000 tonnes of salmon in net-pens.

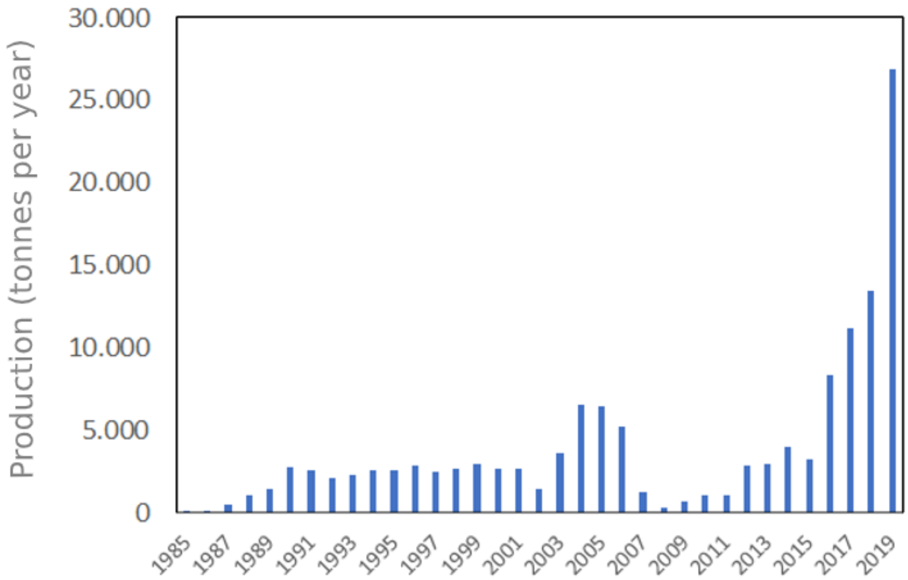


Figure 1.5 Production of farmed Icelandic salmon during the period 1985-2018 (www.mast.is).

1.6 Accidental release and farmed escapees in Iceland

During the early years of salmon farming in net-pens in Iceland in the late eighties, farming equipment was primitive and there were frequent accidents. The pens were mainly located in the bay Faxaflói (close to Reykjavík) and the escapees entered rivers close to the farm areas (Gudjonsson, 1991; Gudjonsson et al., 2005).

In the year 1988, the proportion of farmed salmon peaked at 30-40% in the rivers Ellidaá and Leirvogsá and over 60% in river Botnsá in Hvalfjördur (Vidarsson and Gudjónsson, 1991, 1993). At the same time, fish from the sea ranching station at Kollafjördur also went up the rivers in Faxaflói (Gunnarsson, 2002, 2007). All farmed fish were of Icelandic origin at this point and the intrusion of farmed fish was not regarded as a particularly serious problem. The farmed salmon was most often identified from appearance (eroded fins and cuttings), but scale reading was used to obtain a more accurate analysis (Jónsson and Antonsson, 2004).

In the second wave of salmon farming in the years 2002-2006, the farming companies had switched to Norwegian strain (Gudjonsson and Scarnecchia, 2013). During this period, one accidental escaping of farmed salmon was reported (August 20, 2003), when 2,900 grow-outs escaped in the harbour of Neskaupstadur. The fish had been transported by a well-boat from the net-pens in Mjóifjördur, where it had been reared since July 2002. An attempt was made to recover the fish with gillnets, but only 109 salmon were recovered. Of recovered salmon, 14% showed signs of maturation. Most of the salmon were caught in Nordfjördur Bay in and near the harbour where the farmed salmon escaped and other 9 were caught in Mjóifjördur. In September, 10 additional fish were caught in salmon rivers in the fjords on the east coast of Iceland. Six of these fish swam about 70 km south and were caught in the river Breiddalsá. The other four fish swam about 120 km north to Vopnafjördur where three were caught in the river Hofsá and one in the river Selá. It is noteworthy that farmed salmon were not caught in any of the Arctic char rivers, but only entered the salmon rivers in the area. No catches were reported the following year. A total of about 4% of the escapees were recovered, but only 0.4% in salmon rivers (Jónsson and Antonsson, 2004; Gunnarsson and Beck, 2003b).

This incident gives some interesting information about routes and survival of escapees. Firstly, it indicates that the survival of late escapees seems to be low and few salmon enter the rivers to spawn when the pens are located far from a river. Second, some escapees swim long distances until they find a salmon river. Thirdly, escapees can search in both directions along the coastline, not only in the direction of the coastal current.

In the third and current wave of salmon farming, three accidental releases of farmed salmon have been reported. The first event took place in November 2013 when 200 farmed salmon escaped through a hole in a pen of the company Fjardalax in Patreksfjördur. Next summer, 21 farmed salmon were caught in Kleifaá in Patreksfjördur but Kleifaá is not a natural salmon river. Attempts to recapture more fish with gillnets and fishing rods gave a total of 43 more escapees (Gudmundsson et al., 2014; Gudmundsson, 2014). No reports have been received on escapees in nearby fjords. However, it should be noted that it is difficult to notice minor leakage from sea cages (Gudmundsson et al., 2017).

1.7 Studies on genetic introgression of farmed fish into Icelandic salmon stocks

Genetic introgression of farmed fish to natural Icelandic salmon stocks was confirmed when salmon stocks were examined in the Ellidaá river system (Ellidaár, Hólmsá and Sudurá) (Gudmundsson et al., 2013). The results demonstrated a genetic difference between all three rivers internally, which was considered a remarkable outcome for such a small system. In the study, hybrids (juveniles) of wild salmon and farmed salmon were found in the years 1990-1991 and 2005, even though farmed salmon had not been observed in the river since 1999. It was thought that hybrids of previous years had managed to return to in the rivers as mature fish and have off-springs.

1.8 Genetic introgression in Norway

The extent and impact of genetic introgression on wild Norwegian salmon stocks has been assessed (Glover et al. 2017) after the fifty-year history of salmon farming in Norway, where salmon lice and genetic introgression are the two biggest problems facing the industry. The article gives a detailed account of the state of knowledge in this field and discusses the history and status of genetic introgression in other countries, especially Ireland.

Although it was a formidable task to estimate introgression of farmed salmon in wild populations, where they are not exotic, a new panel of SNP markers was identified that could differentiate between farmed and wild Norwegian salmon (Karlsson et al., 2011). The study covered populations from 147 salmon rivers, representing three-quarters of the total wild salmon spawning population in Norway. In 109 rivers, with adult samples and sample sizes of 20 or more, the average level of farmed genetic introgression was 6.4% (median = 2.3%), with a range of 0.0 - 42.2%. Fifty-one of these rivers showed significant farmed genetic introgression when compared with historical reference samples (Karlsson et al. 2016). It has been suggested that the density of the native population is probably a major factor affecting the level of introgression, via spawning (Fleming et al., 1996) and thereafter comes juvenile competition (Fleming et al., 2000; McGinnity et al., 1997; Skaala et al., 2012).

If the density of wild spawners is high, the competition will be high during the spawning season, and the farmed matured fish are outcompeted by wild fish which results in less introgression. Genetic introgression may alter various factors such as growth rate of juveniles, time of smolting, growth rates in seawater phase and the onset of maturation. Studies suggest that genetic introgression will influence phenotype and life history of the wild stock and move it toward the characteristics of the farmed fish (Bolstad et al., 2017). However, it can be difficult to identify these changes due to other factors such as climate change. Modelling work has shown that variability between strains will be reduced due to mixing with farmed fish (Liu et al., 2013; Castellani et al., 2018).

1.9 Available data on the number of escapees and their spawning success in nature

1.9.1 Assessment of the number of escapees in Norwegian salmon farming

In salmon farming, the number of escapees is commonly estimated as a percentage of the production volume, usually as number of fish per tonne produced.

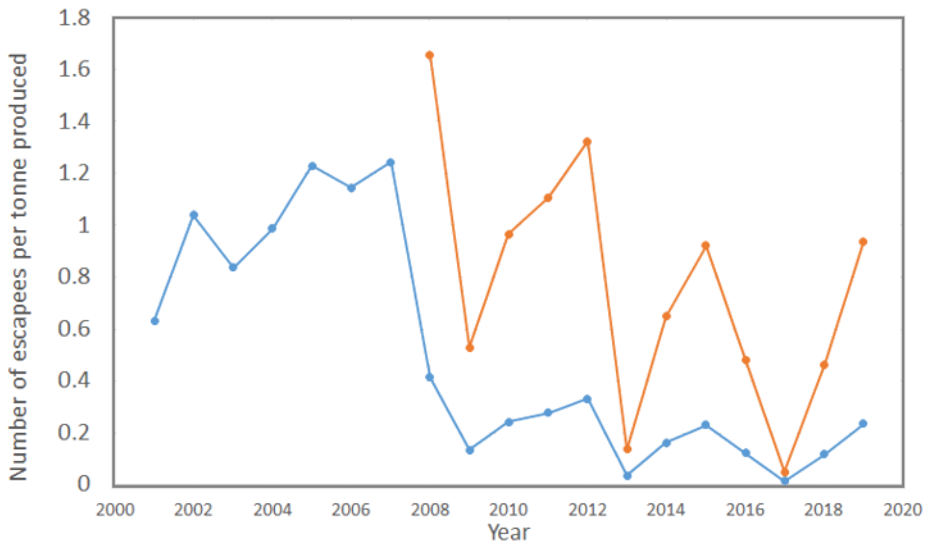


Figure 1.6 Number of escaped salmon in Norway - the number of individuals per tonne produced. The blue line shows reported releases and the red line shows the estimated total number of escapees (multiplication by a factor of 4).

It is known that the actual numbers of escapees are higher than the reported figures. A meta-analysis of catch statistics and tagging studies suggested that the actual numbers of escapees in Norway were 2–4 times higher than reported numbers in the period 2005–2011 (Skilbrei et al., 2015). Also, some relatively large unreported escape events seem to have occurred (Glover et al., 2008; Glover, 2010), it has also been suggested that smaller un-noticed or un-reported escapes, so-called trickle escapes, make up a significant proportion of escapes not included in the official statistics (Skilbrei et al., 2015). In other countries, the level of underestimation in escape statistics is relatively unknown.

In Norway, the number of escapees since 2008 has been approximately 0.8 salmons per tonne produced per year, assuming that they are four times higher than the reported number (Fig. 1.6). The annual salmon production in Norway has been close to 1.2 million tonnes in the past 5-6 years, corresponding to 330 million fish. Based on a value of 0.8 escapees per tonne produced, escapes are estimated to be up to 1 million farmed salmon per year or 0.3% of the total farmed salmon. When this figure is put in context with the size of the wild stocks, escapees are more numerous than the total number of spawning wild salmon (400-500,000 fish per year). However, only a limited number of escapees enter rivers to spawn. Most escapees are lost at sea where they struggle to find feed and avoid predators. Their breeding success is greatly influenced by the proximity of the farm site to suitable rivers and their age at the time of escape. Most escapees never return to spawn.

1.9.2 Spawning of escapees

In Norway during the years 2014-2015, escapees were more than 10% of the total number of mature salmon in 10-20% of the studied rivers. Over 90% of late escapees that enter Norwegian rivers are mature, but they have poor competitiveness compared with their wild counterparts.

Successful spawning in farmed males is only about 1-3% of their wild counterparts. However, in females, the number is much higher or roughly 30% of wild spawning success. The farmed fish often select other spawning areas and even spawn at a different time, which can reduce the survival of eggs. Usually farmed fish have smaller roe than wild fish of a similar size, but it is known that roe size is important for recovery from sea. However, the farmed fish are often larger than the wild fish in the river and can thus have equally big eggs as wild fish (Fleming et al., 1996, 2000).

1.10 Fitness of farmed salmon

Breeding of farmed salmon began in Norway in 1971 based on selected stocks from many Norwegian rivers and today more than 12 generations of breeding fish have been produced in Norway. The genotype features selected for breeding include rapid growth, salinity tolerance in smolts, late maturation and disease resistance. For the first three decades, a four-year generation span was used, while in 2005, the breeding company AquaGen switched to a three-year generation range, resulting in even faster progress. Today, the salmon genome has been sequenced and molecular genetics are being applied with even faster and more precise results. This increased genetic difference between farmed and wild salmon will probably call for stricter precautionary measures.

Comparative studies on farmed and wild salmon have shown a significant difference between factors such as behaviour, maturation, appearance and disease tolerance, but the difference is greatest in growth rate. The results of trials in-tank studies usually show that the farmed fish is 2-3 times larger at the end of the experiment (Glover et al., 2017). However, there are exceptions, and in some cases, the difference is largely due to parental effects, since the parent fish is not comparable. It is also known that growth rates do not stem solely from genetic selection but also from adaptation to the man-made environment in which the fish must live in. Many studies show that farmed salmon are better adapted to the aquaculture environment and the wild ones better adapted to nature.

Comparative studies in nature have shown better performance of wild compared to farmed salmon. For such a comparison, it must be taken into account that only 1-2% of the roe is expected to become smolt and less than 10% of the smolt returns to the river. Wild salmon usually stays only one winter in the sea, but the farmed fish normally longer. This explains less survival of farmed salmon than wild salmon. A study in the River Imsa in Norway using comparable parents (1-2 winter in the sea), poor competitiveness of farmed salmon was demonstrated. The spawning performance of the farmed fish was less than one-third of the wild fish and the fitness of the farmed fish was only 16% of the fitness of the wild fish (fitness = maintenance of the stock size of spawning fish in the river from generation to generation). The carrying capacity of the river was a limiting factor and therefore the incorporation of the farmed fish had the effect of reducing the annual production of the river by 30%. However, in this study there was no significant difference in survival at sea or age at maturity (Fleming et al., 2000).

Fertilized eggs were planted in a salmon river with an increasing density over a period of three years (Skaala et al. 2012). The results showed that survival of juvenile fry decreased with increased roe density. This indicates that the fish farms have reduced competitiveness and therefore have less survival if the juvenile density in the river is high. At the same time, this suggests that juveniles from escapees have higher survival in rivers with lower egg density and thus less competition.

1.11 Modelling work

To understand how the process of introgression might work, several models have been developed to study the effect on different levels of introgression on the population, such as the OMEGA model (Blair and Jason, 2014) and the IBSEM model (Castellani et al., 2015).

A recently published modelling work on fitness changes in wild Atlantic salmon populations faced by spawning intrusion (Castellani et al., 2018) indicates that natural selection will be able to resist some introgression as long as the model is a purely additive model. The model shows that there will be a point where this will result in changes and ultimately collapse. It is important to bear in mind that a model, which is trying to understand what may happen, does not account for additive parameters that in a real situation can give unexpected results. This can be the case in the farming of Norwegian salmon in Iceland with even more differences between genotypes of wild versus farmed fish than in Norway. Modelling work shows that even low introgression alters genotype frequency in wild populations but does not affect fitness if it is small enough.

A model for survival, distribution and intrusion can prove to be a valuable tool, especially in Iceland where farming of Atlantic salmon is still limited but is expected to increase substantially in the coming years. It can be used as a guideline on how to position the farming site to minimize the risk of introgression.

2. Methods

2.1 A model for the assessment of intrusion risk.

This report presents a new risk assessment model for the intrusion of farmed salmon into salmon rivers. The purpose of the model is to estimate the number of escapees that might be involved in each spawning season. The number of farmed escaped salmon is directly related to the risk of genetic introgression (Glover et al., 2012, 2013), and therefore chosen as an indicator to estimate the risk of genetic changes in each wild population. If the intrusion rate exceeds certain a threshold each year, there is a risk that genetic introgression may accumulate at a higher rate than natural selection can sort out.

In the Icelandic model, the threshold values for farmed fish intrusion were chosen following Taranger et al. (2015). The lower threshold value of 4% intrusion corresponds to the lower part of the natural straying estimates and carries limited risk of genetic change to the population. The higher threshold value of 10% intrusion reflects a limit for the high risk of genetic change to the population. It must be considered that the genetic difference between Icelandic wild strains and the Norwegian farmed strain (SAGA stock) is higher than that between farmed and wild strains in Norway and therefore the threshold values should probably be chosen more stringent for Iceland.

The aim is to ensure that the production of farmed salmon in net cages does not adversely affect wild stocks. As many variables are uncertain due to lack of data, we propose to evaluate the risk of genetic introgression by an interactive risk model based on the results of the monitoring program that will be performed annually. In this way, salmon farming regulation can be based on the latest information to minimize the environmental impact of the industry.

The process of genetic introgression can be divided into two stages: (i) escape of farmed fish from sea cages and the likelihood of run into a river; (ii) their reproduction in the river, the life history of offspring (pure farmed and hybrids) and their effect on the genetics of the stock. Separate models are to be used to predict each of these two stages. Current models have been made to predict the process of the second stage, i.e. introgression of farmed salmon into wild stocks (Castellani et al., 2015, 2018, Verspoor, 2017), but to our knowledge, this is the first model describing the intrusion of farmed salmon.

In Norway and Scotland, salmon farming is dense, close to rivers and has been going on for decades. Therefore, a model for the intrusion of farmed salmon has not been practical in these countries. However, in Iceland, the salmon farming areas are generally far from salmon rivers, and the path and distribution of escapees is of great importance. Furthermore, fjords close to the main salmon rivers are closed for salmon farming to protect natural populations from genetic introgression, parasites and diseases (Gudjonsson and Scarnecchia, 2013). It is thus of great importance to model the extent of migration of farmed fish to evaluate the intrusion risk. As farming of Atlantic salmon in open net pens is in its infancy in Iceland, there is an opportunity to monitor the intrusion risk as the industry grows.

The model is therefore valuable in Iceland to evaluate the effects of fish farming on wild salmon stocks in Iceland. The model has recently been implemented in Newfoundland (Bradbury et al., 2020) to estimate the effects of the proposed increase in salmon farming. Farming of salmon is confined to specific zones in Iceland, far from the valuable salmon rivers to minimize the effect of farming on the wild stocks. This will shed light on variables such as the number of escapees, survival rate, behaviour and life history of salmon in the sea. Technical advances in genetic research make it possible to monitor the distribution and survival of escapees from individual farming sites. The model estimates the effect of all farms on all rivers in which the stock size can be estimated, both in number and as a percentage of the brood stock of the river.

The development of the risk assessment model was based on best available information from peer-reviewed articles as well as available data sets from Icelandic, Norwegian and Irish reports.

2.2 Available data

The model calculates the number of farmed escapees entering rivers, based on factors that can be divided into three main categories: Geographical-, farming- and life-history factors.

2.2.1 Geographical factors

The model uses geographical factors such as strength and direction of ocean currents, the abundance of fish migration into rivers and river topology. The coastal current around Iceland flows in the clockwise direction (Fig. 2.1).

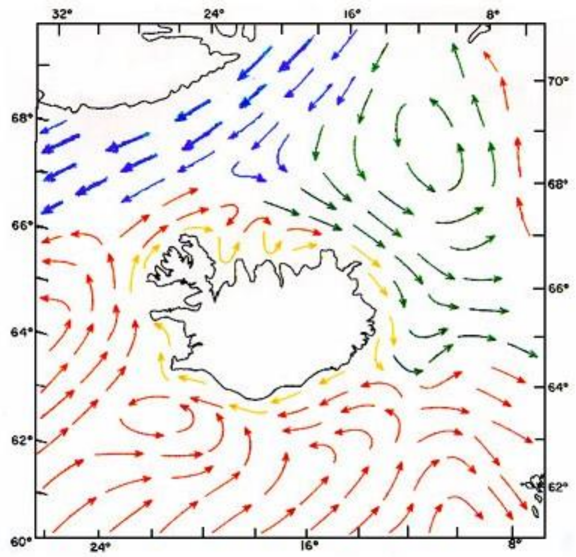


Figure 2.1 A map showing ocean currents around Iceland.

2.2.2 Factors related to farming

Data regarding the aquaculture operations include coordinates of net-pens and other site details, biomass at each site, size and age of the fish reared in the pens and data on escape events. These include statistics of escape frequency and the average number of escapees per tonne produced.

Farming of salmon is only allowed in restricted areas around Iceland, usually in a considerable distance from the main salmon rivers. Those areas were specifically chosen to protect rivers from genetic introgression as advertised by the Ministry of Agriculture in May 2004 (Ministry of Agriculture, 2004). This effectively restricts the potential farming areas to the Westfjords and the Eastfjords (Fig. 2.2).

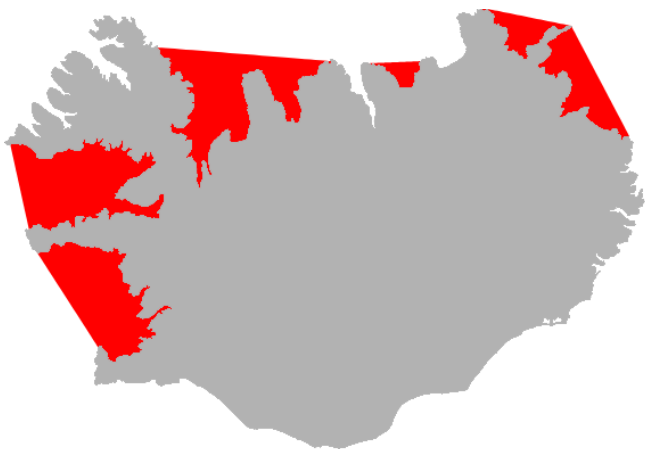


Figure 2.2 Areas around Iceland where salmon farming is prohibited (red). Fish farming is not possible on the south cost and thus the possible farming areas are confined to the Westfjords, Eyjafjordur in the North of Iceland and the Eastfjords.

The model uses accurate data on the number of salmon smolts put in sea pens and the number of fish slaughtered approximately 18 months later. These numbers are obtained from the software, *Fishtalk*, used by the aquaculture companies.

Based on documentation of catch and release data from fish counters (Jonsson et al., 2008), it is assumed in the model that stock size is two times the catch in each salmon river, using average catch during the last ten years.

Fish are vaccinated a few weeks before stocking into pens and vaccination is performed with hand-operated syringes equipped with counters, providing an accurate count of the number of fish in each tank. Usually, fish groups from tanks are not split when stocked into pens which results in good accuracy of fish number. However, if groups are split-up, the fish are counted with fish counters into pens with a lower accuracy or around 2-3% counting error.

The percent loss in number of fish is due to natural mortality and in some cases escape events, which are documented by the companies. We estimated the number of escapees by comparing the loss in sea pens with and without escape events. Daily mort collection numbers seem to have higher uncertainties and were not used in the model.

2.2.3 Life history data

Understanding the behaviour and distribution of the fish after escaping is a crucial part of the prediction accuracy of the model. The behaviour and migrations of smolts differ from those of larger salmon. Therefore, we categorize escapees as *early escapees* if they escape before they reach the average weight of 1.5 kg and as *late escapees* if they escape at a larger size. Wild salmon smolts migrate from the river to the ocean in a relatively short period, then migrate to the feeding grounds and finally return to their home river after 1 – 3 winters at sea. Farmed salmon smolt escapees, on the other hand, do not migrate from rivers and thus have different behaviour when they become mature.

For wild smolts, an imprint of the origin river likely occurs at the time of smolting, since the sense of direction towards the home river is good. How this happens with farmed smolts is not clear. The model assumes that the early escapees return from the feeding grounds to their origin at the farming site where they escaped. They will then select a nearby river for a run. It is a plausible hypothesis that the smell of full-sib salmon from their home net-pens diverts the salmon and delays it in its quest of finding a river as it recognizes the farm site as a river mouth. This hypothesis has yet to be tested.

In Iceland, a long timeseries of data is available on smolt survival from sea ranching rivers such as river Rangá and a shorter series for wild rivers such as river Ellidaá. Salmon smolts of farming origin have on average 37% of the return rate of natural smolts (Hindar et al., 2006). Based on these numbers return rate of smolts of wild origin is assumed to be 5% and farmed salmon estimated as 37% of the return rate of wild smolts. It is further assumed that returning early escapees will be distracted in their homing migration by the smell of fish in their home pen. In the initial version of the assessment model, this behaviour is assumed to prevent some of the fish from entering rivers and thus reduce the return rate. Based on these assumptions, the initial assessment model predicted a 1.85% return rate for early escapees (5% × 0.37 = 1.85%). This value includes the combined return of early escapees after one to three winters at sea.

2.3 Parameters and equations

The risk assessment model is made up from several mathematical equations, based on the assumptions listed above.

2.3.1 The return rates of early and late escapees.

Equation 1 calculates the total number of late escapees from a farming site that are predicted to return and enter salmon rivers.

$$E_G = PS_G \frac{R}{T} M \tag{1}$$

Where

$$\frac{R}{T} M = L_G \tag{2}$$

Equation 1 uses input about annual production (P), the number of late escapees per tonne produced (S_G), survival and maturity at sea (M), total rearing time (T) and risk period (R). The risk period is defined as the timeframe of escape, during which late escapees have a possibility of survival at sea and subsequently entering rivers to spawn. If the fish escapes too early, it is assumed that it will not survive in the wild. If the fish escapes too late, it is assumed that it will not have enough time in the wild to mature and enter rivers to spawn during the following summer. However, as discussed later, the monitoring program has shown that some late escapees can indeed survive a whole winter at sea and return to rivers in the following year. The return rate of late escapees (L_G) is thus calculated as the product of relative risk time (R/T) and maturity rate (M).

Equation 3 calculates the total number of early escapees from a farming site that are predicted to return and enter salmon rivers.

$$E_S = PS_S L_S \tag{3}$$

Equation 3 predicts the total number of returning early escapees (smolt escapees) in a similar manner as equation 1 for late escapees. For the early escapees the likelihood of return (L_s) is used in the equation, instead of the relative risk period for the late escapees. The estimated likelihood of return is based on published scientific papers and reports, as discussed previously.

2.3.2 The homing of early escapees – the homing parameter

It is assumed that returning early escapees will be distracted in their search for their home river by the smell of fish from their old farming site. This has the effect that the farming site acts as a home river distracting some of the fish in their quest for home river and reduces E_s, the number of fish entering rivers.

2.3.3 The distribution of escapees

A Weibull distribution is used as a probability distribution function for migrating fish. The model calculates two distributions of escapees for each farming site, one for early escapees (smolts) and a separate one for late escapees (grow-outs). These two distributions are then merged to form the total distribution from each site. Weibull distribution has two parameters: β and η. The parameter η controls the width of the distribution (scale parameter), in this case how far the salmons migrate from the point of escape, whereas β is the shape parameter and controls the skewness of the distribution. The skewness is used to represent the tendency of the fish to migrate along or against the coastal current around Iceland. Different values for β are chosen for initial values of skewness for early escapes (smolts) and late escapes (grow-outs) in accordance with their behaviour. The farming site is placed at the top of the distribution as zero of the distance axis and positive numbers express distribution with current and negative numbers counter current. The distribution of escapees is described by the Weibull function:

$$\mathrm{W}(V) = \frac{\beta}{\eta}\left(\frac{v_a}{\eta}\right)^{\beta-1} e^{-\left(\frac{v_a}{\eta}\right)^{\beta}} \tag{4}$$

The equation is normalized to give:

$$W = \frac{\frac{\beta}{\eta}\left(\frac{V_a}{\eta}\right)^{\beta-1} e^{-\left(\frac{V_a}{\eta}\right)^{\beta}}}{\sum_a \frac{\beta}{\eta}\left(\frac{V_a}{\eta}\right)^{\beta-1} e^{-\left(\frac{V_a}{\eta}\right)^{\beta}}} \tag{5}$$

Equation (5) calculates the number of fish from age group X which end up in river a, by combining the results from the above equations.

$$F_{aX} = E_X \frac{W_X A_a}{\sum_a W_X A_a} \tag{6}$$

Overall, there are 14 parameters used in the distribution model, as summarized in Table 2.1.

Table 2.1. Parameter descriptions and values.

Parameters	Description	Estimated value
X_G	Value of variable X for late escapees	-
X_S	Value of variable X for early escapees	-
P	Production of farm site in tonnes	-
E	Number of escapees returning to rivers	-
S	Escapees per tonne produced	0.8 escapees/t (50% adults)
R	Risk period (Feb-May)	4 months
T	Total sea time in months	18 months
M	Proportion of late escapees that survive at sea, mature and enter rivers	5%
L	Proportion that survive at sea and enter rivers	1.1% (L_G) 1.3% (L_S)
V_a	Distance from farm site to river *a*	-
H	Homing parameter	0.25
W	Standardized Weibull distribution that estimates the distribution with given β and η	-
A_a	Stock size of river *a*	-
F_a	Estimated number of farmed escapees in river *a*	-

Early escapees are expected to have a more bell-shaped distribution curve and return over a narrower range (<200 km) due to their better homing ability. The distribution curve for late escapees is more skewed towards the coastal current direction and has a wider distribution span (η). The shape factor *(β)* is dimensionless whereas η has a dimension in kilometres. The reason for the different distribution is that smolts (early escapees) behave differently than grow-outs (late escapees). The behaviour of farmed smolts will also differ from their wild counterparts. Wild smolts all leave their home rivers in a relatively short period, usually within a few days and the imprinting to natal stream odours seem to occur during the parr–smolt transformation (Lema and Nevitt, 2004). Other factors such as magnetic field in-printing and collective navigation also seem to be a part of the navigational abilities of wild salmon smolts (Putman et al., 2013; Berdahl et al., 2016). Smolts migrate to feeding areas and eventually return to their natal streams when they mature. On the other hand, it appears that farmed early escapees navigate towards the point of escape, i.e. the net-pen and subsequently enter salmon rivers relatively close by the pen (Putman et al., 2013; Berdahl et al., 2016).

Grow-outs escaping as late escapees have a different behaviour. If they survive to reach maturity during the summer after the escape, they will attempt to migrate up rivers to spawn. They tend to follow the coastal current (Hansen, 2006) in their search for their natal river and can cover long distances, as far as 1000 kilometres (Gudjonsson, 1991; Piccolo and Orlikowska, 2012). Most of them will migrate to rivers close by and the recapture rate of late escapees in rivers is correlated with the amount of farming in the area (Fiske et al., 2006). In Scotland much fewer migrating farmed fish are observed on the east coast (no farming) than on the west coast where farming is practised (Green et al., 2012; Youngson et al., 1997).

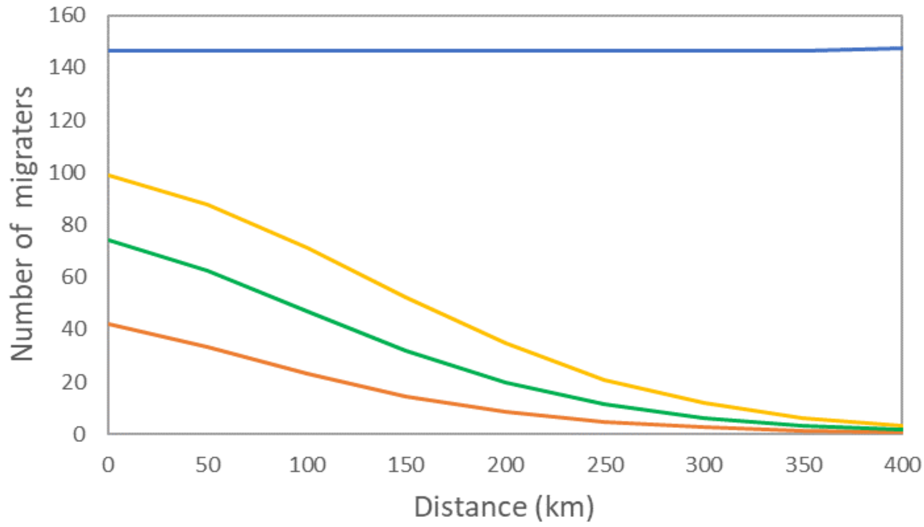
The distance from a farm site to each river in Iceland is measured and each river placed on the Weibull curve with the farm site at the top of the curve. The probability of a fish entering a river at a given distance is scaled proportionally with the stock size in that given river. This means that if two rivers A and B are side by side and river A has twice the stock size of river B, it is assumed that it is twice as likely that the fish enters river A than river B.

2.3 Sensitivity Analysis

We have performed a sensitivity analysis to test how sensitive the model is to changes in the model parameters. The parameters can be split up into three groups. First there are the β and η which control the shape of the Weibull distribution curve. They do not have any effect on how many salmons end up in rivers, only on how they are distributed. For small values of η all the fish migrate to their nearest river but with increasing values of η the distribution gets wider. For small values of β all escapees migrate to rivers down current but with increasing values of β the distribution gets more even, with the escape site in the centre.

In a second group of parameters, they all have a linear effect. Those parameters are: S, R, T, M and L_G. That means that a 10% increase in those parameters will give a corresponding 10% increase in E_G or E_S, respectively. The Homing parameter, however, does not have a linear effect and is heavily influenced by the distance to the nearest river.

Figure 2.3 The effect of the homing parameter (H) on the predicted number of smolt escapees returning to a river as a function of distance. Here, the farm site has a production of 10.000 tonnes and the river a stock size of 1.000 salmons. The blue line is where the homing parameter is 0, yellow is 0.05, green is 0.1 and orange is 0.25.



2.4 Initial estimates of variables

2.4.1 The escape coefficient

There are no available statistics on the number of escapees per tonne produced from Icelandic salmon farming. Since the same standards for farming equipment and work routines are used in Iceland and Norway (NS 9415:2009), it is assumed that the relative number of escapees is similar in both countries. Norwegian authorities have for many years published an annual summary of the number of reported escapees, presented as number of escapees per tonne produced (Fiskeridirektoratet, 2019a,b). We adopted the Norwegian values for our initial model and used the average number of escapees over 9 years, i.e. from 2008-2016. The justification is that the standard NS 9415:2009 was imposed in 2009 but was commonly used somewhat earlier and a sharp reduction was observed in 2008, which can be related to the implementation of the equipment according to this new standard.

As mentioned earlier, it is estimated that the actual number of escapees may have been 2-4 times higher than the reported number (Skilbrei et al., 2015). Genetic studies suggest that scattered escapes (leaks) are the main reason for this underestimation in public figures. In recent years, there seems to have been a significant reduction in the leaks, probably due to stricter regulations and better farming equipment. In the initial risk assessment, the reported number of escapees in Norway was multiplied by a factor 4, producing an average escape coefficient (S) of 0.8 escapees per tonne produced during the period 2018 – 2016.

The ratio of early and late escapees is assumed here to be 50:50. This ratio has been used in the genetic engineering model from NINA (Hindar et al., 2006). The basis is a study of the proportion of astaxanthin pigment in the tissue of farmed escapees ascending two Norwegian rivers in the autumn of 1991. The astaxanthin content fell into two distinct classes. Fifty-one per cent of the adult escaped salmon had isomeric ratios similar to salmon fed synthetic astaxanthin, whereas all the remaining fish had ratios typical of wild salmon (Lura, 1994). The amount of astaxanthin thus fell into two categories, either a similar level as in farmed fish or a similar level as in wild fish. This, together with other factors, indicated that the ratio between early- and late escapees had been around 50:50 during the period of investigation. In the initial version of the risk assessment model, a 50:50 ratio was used, i.e. 0.4 smolt escapees and 0.4 grow-out escapees per tonne produced per year.

Thus, given the yearly production of 13,500 tons from ocean-based Icelandic salmon farming in 2018 and using a value of 0.8 for the S coefficient, approximately 10,800 escapees were predicted from Icelandic marine farms in 2017, half as early escapees (early escapees = <1,5 kg) and half as late escapees.

Table 2.2. The yearly numbers of reported salmon escapees per tonne produced, according to the Norwegian Directorate of Fisheries. The reported number is multiplied by a factor 4 in the last column. The average values and standard deviations are indicated at the bottom.

Year	Escapees/ton	x4
2008	0.41	1.65
2009	0.13	0.53
2010	0.24	0.97
2011	0.28	1.11
2012	0.33	1.32
2013	0.03	0.13
2014	0.16	0.65
2015	0.23	0.92
2016	0.12	0.48
$\bar{\mu}$	0.22	0.86
σ	*0.11*	*0.44*

2.4.2 Parameters for rivers

The proportion of migration: Salmon have long been known to imprint and home to natal stream odours using their olfactory senses (Lema and Nevitt, 2004). In this model, it is assumed that fish will search rivers in proportion to the size of the salmon stock in the river i.e. in proportion to the concentration of salmon odours although not necessarily the odour from their family members.

2.5 Parameters for early escapees

2.5.1 Weibull shape parameter β

This parameter controls the shape of the distribution curve. A value of 2.5 was used in the initial version of the model, which gives a symmetrical distribution from the point of escape.

2.5.2 Weibull scale parameter η

The initial version of the model assumes that escapees will not migrate much further than a 200 km circle from the escape site. However, the navigation abilities of smolts of Norwegian genotype could be possibly be different from wild Icelandic fish, which would affect both seawater life history and the accuracy of return. Controlled releases with tagged fish will be needed for better estimates.

2.5.3 Homing Coefficient (H)

We assume that a returning fish experiences its old farming site as a home river due to strong salmon odour of related fish. This leads to their reluctance to leave that site. To account for this the model treats the farm site as one of the rivers and the fish that migrate to the farmsite do not enter any real salmon rivers. The stock size of the farm site (pseudo river) is estimated as:

$$A_{farmsite} = HP \qquad (7)$$

The homing coefficient (*H*) has the unit (number of fish)/(1000 tonnes). As a first estimation, we assume that the attraction is equivalent to a simulated river with a fish stock equal in number to 25% of the biomass at the farming site, i.e. if we have a farming site with a 1000 tons biomass it will act as a river with 250 fish and reduce the number of migrating fish accordingly.

This coefficient has non-linear effect with farming size and distance as shown in Figure 2.3. The usefulness of such a coefficient becomes clear if we study the case of a farming site far from salmon rivers and the small probability of migration over far distances. However, if no rivers are close to the farm site, unrealistically all are predicted to enter these rivers (Fig. 2.4). To dampen this artifact the Homing Coefficient was introduced. The use of this coefficient is equivalent to a part of the late escapees never leaving the farming site. This coefficient must be adjusted in future versions through research trials.

2.5.3 Return rate of early escapees (1-3SW) (L_S)

In our first version of the model, the return of early escapees was estimated based on the return of natural juveniles as a reference. It was also based on the ratio between farmed and wild return according to release trials in the river Burrishoole in Ireland (McGinnity et al. 1997, 2003) and in the River Imsa in Norway (Fleming et al. 2000). In these studies, the relative survival of farmed and wild juveniles was monitored from spawning to return to the river. On average, the relative return rates of farmed juveniles equalled 37% of the return rate of wild juveniles. In Iceland, measurements show that the return of wild juveniles varies by region. In general, the return is lower in the north than in the south part of Iceland. This is seen from the data on return to the river Ellidaá (South-west) and Vesturdalsá (North-east). The average return to river Ellidaá in the period 1988-2016 was 8.9%, while the return after 1SW to river Vesturdalsá during the years 1996-2016 was 2.2% (ICES 2019). In the risk assessment model, the average return rate for these two rivers (about 5%) is used for 1SW return of wild fish. Based on the aforementioned studies (Fleming et al. 2000, ICES 2019), the risk assessment assumed an early escapee return rate of 5% × 0.37 = 1.85%. The Homing Coefficient will then lower the return rate as a function of farming scale, i.e. more biomass at the farm site will decrease the relative number of fish entering rivers.

In the current re-evaluation, the return rate was based on recapture rate as a function of post smolt size, derived from extracted data from Skilbrei et al. (2015). The ratio L_S was lowered to 1.3% (see chapter 3.1.5.).

2.6 Parameters for late escapees

2.6.1 Weibull shape parameter β

Initial estimates of β for late escapees were set so that approximately 65% of the fish would enter rivers clockwise from the release point (farm-site) and subsequently 35% counter-clockwise. This was achieved by setting β = 2. Data from Norway and Canada were used as a first estimate for the model (McGinnity et al., 1997; Fleming et al., 2000), but results from the first year of the monitoring program have now given the first results to revise the parameters. Geographical factors can affect the distribution so that different parameters could apply for different farming sites but for this first version of the model every farming site is estimated to have the same distribution.

2.6.2 Risk period (R)

The risk assessment includes a so-called risk period for late escapees. Fish that escape during this period, survive the winter and become mature for migration and spawning that following summer. If the fish escape too early they are not expected to survive the whole winter and if they escape too late, the artificial light in the pens will prevent maturation. We assume a risk period of around 4 months from November - February. This is an initial estimate since limited data is available. It provides support to the assumed risk period that all but one of the 2018 migrating escapees that were traced to an event on February 11, were mature at recapture.

The average rearing time in pens in Iceland is 18 months and the risk period (4 months) thus equals 22% of the total seawater phase. Longer monitoring is needed to adjust the duration of these periods in the model. In the revision of the model, equation (2) is no longer used for the calculation of L_S.

2.6.3 Maturity ratio of grow-outs (M)
The risk assessment includes a so-called maturity ratio for late escapees. This parameter reflects the proportion of late escapees, escaping during the risk period, that survive in the wild and eventually migrate to rivers to spawn as mature salmon. Even though these escapees may not be mature at the time of escape, they may have enough time in the wild to mature and migrate to rivers. In the initial assessment, the maturity ratio was set at 15%, meaning that 15% of the fish escaping during the risk period were predicted to survive in the wild and migrate up rivers to spawn. In the present re-evaluation this is no longer used.

2.6.4 Return rate of late escapees (L_G)
As explained in the previous section, the return rate of late escapees is calculated by the model as the product of relative risk time and survival probability in the wild. As explained previously, the return rate of late escapees is calculated according to equation (2), $L_G = R/T \times M$. The first version of the model assumed a 15% maturity ratio, and thus a 3.3% return rate for late escapees ($L_G = R/T \times M$ = 4/18 x 0.15 = 3.3%). The present version, L_G is estimated based on monitoring results and analysis of monitoring data and reports on Norwegian late escapees (see chapter 3.1.6). The model has now been revised and the use of relative risk time (R/T) and maturity rate (M) has now been discontinued. The return rate of early escapees (L_G) is now estimated directly as 1.1%, based on research and monitoring.

2.6 Monitoring

2.6.1 Riverwatcher monitoring

Key rivers in Iceland are monitored with the so-called *Riverwatcher* camera system (Vaki ohf). The country is divided into five regions and a few key rivers are monitored with *Riverwatcher*-C type or RW-C which consists of an IP underwater stereo video camera with infrared vision, underwater infrared and white LED lights, a stainless steel camera tunnel, and a high-performance computer that counts and monitors the fish. The standard tunnel is 160 x 105 x 63 cm (L x W x H) and is fitted with the underwater digital camera and lights. The standard opening is 40 cm.

Figure 2.4 Screen-shot from the Riverwatcher accessible from the website of the Marine and Freshwater Research Institute (https://www.hafogvatn.is/is/rannsoknir/voktun-veidiaa/ar-og- eldi).

The tunnel ensures that the images are captured under controlled and constant lighting conditions, as well as at the optimum distance of the fish from the camera. Live video from the camera can be viewed in real-time on the RW-C computer screen. Any device connected to the internet can also display a live stream or a looping recording of the last fish seen. The system is equipped with automatic fish identification software to identify size, direction, type of fish and condition, e.g. sea lice, although the detection of lice is still under development. From these videos it can be determined if the fish is of farmed origin. This applies to late escapees; early escapees can be more difficult to distinguish. The monitoring system will be set up in 12 rivers; six blue-marked rivers, already installed, and six red-marked rivers, planned within the next 3 years (Fig. 2.6).

Figure 2.5 The rivers in the Riverwatcher monitoring program. Blue marks rivers that already have a

Riverwatcher and red rivers that will get Riverwatchers in the future

2.6.2 Genetic monitoring

In Icelandic regulations for fish farming (401/2012), salmon egg producers are obliged to preserve tissue samples for DNA analysis of all parent fish used, and to keep records of offspring from each parent pair to allow full traceability from smolt farm to net-pen. Therefore, it is possible at any time to trace the origin of recaptured escapees from cages or smolt stations. Every male sire can be used to fertilize about 100 000 eggs, and each female produces on average about 10,000 eggs. It proved sufficient to genotype all male sires of the 2015 cohort to trace all escapees. Fish farming companies are obliged to report to the Icelandic Food and Veterinary Authority all incidents such as escape events. They are obligated to send in a report with:

1. Estimated timing and location of accidental release.
2. Fish species, average size and estimated number of fish released.
3. Information on drug use and excretion time of the drugs.
4. The origin of the fish in terms of stock and fish farm (i.e. smolt farm).
5. When the fish was taken into the farm or stocked in the net-pens.
6. Causes or probable causes of accidental release.
7. Report on the results of fishing on farmed fish which escaped.
8. An account of what measures will be taken to prevent more fish escaping.

DNA sampling of suspected escapees: DNA samples along with all information regarding suspected escapees caught in angling rivers are gathered. A protocol for sampling has been set up and sampling kits with QR coded vials sent to main angling rivers. The requested information includes river and date, exact fishing spot, size, picture of fish, picture of fishing spot, picture of QR-code of sampling vial. Furthermore, scale samples are requested or the whole fish if possible. Samples are in the form of swabs from gills. Sampling takes a few seconds and does not affect fish survival.

Sampling of fingerlings with electrofishing Every year around 120 fingerlings are fished with electrofishing from rivers in the sampling program. DNA samples are taken from the fingerlings for genotyping. The following rivers are in the program:

Figure 2.6 The rivers in the electrofishing program.

DNA analysis The DNA samples were analysed using a set of multiplex assays (SalPrint15) for the analysis of 15 microsatellite loci of the Atlantic salmon (*Salmo salar*) developed and described by Olafsson et al. (2010). SNP-panel is currently in development, as well as using RAD sequencing.

3. Results

We propose a simple model to predict the intrusion of farmed salmon escapees from sea cages into rivers with wild salmon stocks. Best available data is used to predict migration patterns, survival probabilities and homing success of farmed escapees. The model is intended for management purposes, to aid the administration of salmon farming. It presents a visual tool for monitoring farmed intrusion and gives a clearer picture of the needs in monitoring programs. The model can potentially explain how the predicted intrusion may be affected by changes in various farming-based parameters used in monitoring programs. This Risk Assessment Model for introgression was confirmed as a new amendment into Icelandic law on fish farming on July 1, 2019.

3.1 Results from monitoring

3.1.1 Reported escape events

A total of five escape events were reported by Icelandic salmon farmers during the years 2018 – 2019, all by the company Arnarlax. Three escape events were reported in 2018. Two events occurred on February 11, 2018, one in Arnarfjördur (Hringsdalur farming site, mean weight of escapees 7.2 kg) and the second one in Tálknafjördur (Laugardalur farming site, mean weight of escapees 3.5 kg). The third incident was reported from the same site in Tálknafjördur on July 6, 2018 (Laugardalur farming site, mean weight of escapees 3.5 kg). Two escape events were reported in 2019 but in both cases, the fish were small (mean weight 250g and 1.3 kg) and are not expected to return until 2020 (Table 3.1).

Table 3.1. An overview of escape events reported by Icelandic salmon farmers in the years 2018 and 2019.

Company	Fjord	Farming site	Event date	Report date	Escape estimate	Average size
Arnarlax	Arnarfjördur	Hringsdalur	11.2.2018	12.2.2018	0	7.2 kg
Arnarlax	Tálknafjördur	Laugardalur	11.2.2018	12.2.2018	0	3.5 kg
Arnarlax	Tálknafjördur	Laugardalur	6.7.2018	7.7.2018	300	3.5 kg
Arnarlax	Arnarfjördur	Hringsdalur	21.1.2019	22.1.2019	0	1.3 kg
Arnarlax	Tálknafjördur	Laugadalur	16.8.2019	17.8.2019	0	280 g

The initial assessment by the company predicted 300 escapees from the July incident but no escapees were predicted from the other incidents.

3.1.2 Reported escapees in rivers

Anglers are aware of the observable characteristics of farmed salmon and are willing to report if they are caught. Pictures of suspected farmed escapees are frequently shared on social media for fellow anglers' consultation. We anticipate that over 90% of fish with external farmed characteristics are reported. This will include all late escapees. No early escapees have been reported sofar. A total of 69 DNA samples were taken from reported suspected escapees in the years 2018 and 2019. Analysis with Structure Software (Pritchard et al., 2000) using 14 of the SalPrint15 microsatellites (Olafsson et al., 2010) confirmed that 18 of the fish were of farmed origin.

These fish were compared to potential fathers from the 2014, 2015 and 2016 cohorts, using an in-house program to match the genotypes of fathers (breeding males used by smolt producers) to those of the escapees (see supplementary data). Fifteen of the 18 reported escapees could be traced to one father (Table 3.2).

Table 3.2. Tracing of sampled escapees to their original smolt farm and their farm site at sea. Fish caught in the years 2018 and 2019.

Escapee no.	River (location)	Smolt farm (company)	Site Name (fjord)	Date
F2018001	Selá (Ísafjördur)	Bæjarvík, (Arnarlax)	Laugardalur (Tálknafjördur)	24.7.2018
F2018002	Stadará (Steingrímsfjördur)	Ísthór (Arnarlax)	Hringsdalur (Arnarfjördur)	30.7.2018
F183110	Stadarhólsá/Hvolsá (Breidafj.)	Bæjarvík, (Arnarlax)	Laugardalur (Tálknafjördur)	18.8.2018
F181303	Mjólká (Arnarfjördur)	Bæjarvík, (Arnarlax)	Hringsdalur (Arnarfjördur)	31.8.2018
F181304	Mjólká (Arnarfjördur)	Not confirmed	SAGA (Stofnfiskur)	31.8.2018
F183504	Vatnsdalsá (Húnaflói)	Bæjarvík, (Arnarlax)	Laugardalur (Tálknafjördur)	31.8.2018
F183503	Eyjafjardará (Eyjafjördur)	Bæjarvík, (Arnarlax)	Hringsdalur (Arnarfjördur)	6.9.2018
F183113	Breiddalsá (Breiddalur)	Not Icelandic	Salmobreed	15.9.2018
F2018009	Laugardalsá (Ísafjardardjúp)	Bæjarvík, (Arnarlax)	Hringsdalur (Arnarfjördur)	16.9.2018
F2018010	Fjardarhornsá (Breidafj.)	Bæjarvík, (Arnarlax)	Hringsdalur (Arnarfjördur)	25.9.2018
F2018011	Fífustadadalsá (Arnarfjördur)[2]	Bæjarvík, (Arnarlax)	Hringsdalur (Arnarfjördur)	15.10.2018
F2018012	Fífustadadalsá (Arnarfjördur)[2]	Bæjarvík, (Arnarlax)	Hringsdalur (Arnarfjördur)	15.10.2018
F192520	Ytri Rangá (South Iceland)	Not Icelandic	SAGA (Stofnfiskur)	15.8.2019
F192504	Mjólká (Arnarfjördur)	Ísthór (Arnarlax)	Hringsdalur (Arnarfjördur)[1]	30.8.2019
F192513	Mjólká (Arnarfjördur)	Ísthór (Arnarlax)	Hringsdalur (Arnarfjördur)[1]	30.8.2019
F192514	Mjólká (Arnarfjördur)	Ísthór (Arnarlax)	Hringsdalur (Arnarfjördur)[1]	30.8.2019
F192503	Mjólká (Arnarfjördur)	Bæjarvík (Arnarlax)	Hringsdalur (Arnarfjördur)[1]	30.8.2019
F192515	Mjólká (Arnarfjördur)	Bæjarvík (Arnarlax)	Hringsdalur (Arnarfjördur)[1]	30.8.2019

[1] Not clear if the location was Hringsdalur og Laugardalur. Authors find Hringsdalur more likely see later.

[2] Information about salmon in Fífustaðadalá was published by mistake on the website of the IMFR on the 21st. December 2018. The samples were property of Laxfiska ehf, and institute regrets this mistake.

Three of the escapees could not be traced to fathers of the year-classes 2014-2016 (Table 3.2). Microsatellite analysis (SalPrint15 with Structure software) shows that two of the fish belong to the SAGA stock, i.e. come from Stofnfiskur (F181304 and F192520). Scale analysis of F181304 fished in Mjólká shows that the fish had been at least one winter at sea. It must be noted that if an escapee has access to fish feed during the winter, i.e. stays close to net-pens and feeds on excess pellets, scale reading is not decisive, and the fish can possibly be older. There was not a match between F181304, and the males used in 2014-2016. A plausible explanation is that the fish stems from an older parent, i.e. from a male used in 2013 or earlier.

The fish caught in Breiddalsá (F183113), could have be linked to one of four different brood stocks (Stofnfiskur, Aquagen, Salmobreed and Mowi). A full analysis showed that the fish could be matched with fish from the Salmobreed stock. All salmon produced in Iceland are of the SAGA stock. This confirms that the fish F183113, caught in the river Breiddalsá, was of foreign origin, possibly from the Faroe Islands, although Scotland or Norway cannot be excluded.

The fish from Ytri Rangá (F192520) could be matched with Stofnfiskur through ONCORE analysis. However, it did not match the fathers from 2014-2016 used in Iceland. It is related to the 2014 fathers but is not a direct descendant. This fish seems therefore not to be of Icelandic origin.

3.1.3 Number of escapees from farms

There were three reported escape events in 2018 (Table 3.1) and all the fish caught in rivers during 2018 and 2019 stemmed from these events. Two events were reported in 2019, i.e. February 2019 at the location Hringsdalur, Arnarfjördur (Arnarlax, mean weight 1.3 kg) and in August 2019 at the location Laugardalur, Tálknafjördur (Arnarlax, mean weight 280 g). To date, no fish have been caught in rivers from these events. Fish that escape at such a small size are not expected to return to rivers until at least one year after escaping.

It is not straightforward to calculate the number of escapees from a single escape event. Even though some of the escapees are recaptured in nets in some cases, it is unlikely that a high percentage is recaptured that way, since such measures are often implemented long after the incident. The only way to estimate the number of escapees from a sea cage is through a very accurate account of stocking, harvesting and routine losses. In some cases, such an account is either not possible or not available, and the counting of routine losses is potentially inaccurate. However, in the case of the Icelandic escape events, it was possible to perform a reasonably accurate estimation for one of the incidents.

The three reported escape events in 2018 were from Arnarlax (Table 3.1). At Arnarlax the smolts are vaccinated manually and the dose injectors equipped with counters so that the actual count into net-pens is reliable. As a rule, fish from tanks are usually not split up before being transported to pens which should mean that stocking numbers into pens are accurate. Harvest numbers are equally reliable as harvest lines are equipped with accurate counters. During the production process, dead fish are collected and counted from the pen’s dead fish collector but these numbers are not accurate. Data from the Arnarlax site Steinanes, where no incidents had been reported and no escapees observed, was used to estimate average losses and routine mortality variation between pens. Total fish mortality was assessed based on harvest count only since the routine mortality count proved highly inaccurate for almost all the cages. As no escape events had occurred at this site, the mortality data were used to estimate the average and standard deviation of fish loss due to routine mortality. Mortality was unusually high at all farming sites due to underlying bacterial kidney disease (BKD) at the time (Table 3.3).

Table 3.3. Reported fish mortality from pens at the Steinanes farming site. Only these pens were stocked with a known number of smolts, with no split-up before stocking The average and standard deviation are indicated below the table.

Unit (nr.)	Stocking (number)	Harvest (number)	Loss (number)	Loss (%)
05	172,100	141,137	30,963	18.0%
07	183,192	148,857	34,335	18.7%
08	194,100	168,093	26,007	13.4%
09	183,000	138,500	44,500	24.3%
10	222,432	180,650	41,782	18.8%
11	187,612	150,125	37,487	20.0%
			μ	18.9%
			σ	3.2%

Table 3.3 shows that the routine losses were relatively similar in all six cages at the Steinanes site, with an average loss of 18.9% and a standard deviation of only 3.2%. The routine losses at the Steinanes site served as a reference point for the site at Hringsdalur where two escape incidents were reported (in cages nr. 2 and nr. 6) (Table 3.4).

Table 3.4. Data from site Hringsdalur. Escape events were reported from cages nr. 2 and 6. Escapee numbers were assessed from cage nr. 2 (highlighted). The average and standard deviation of all cages, except cage nr. 2, are indicated below the table.

Unit (nr.)	Stocking (number)	Harvest (number)	Loss (number)	Loss (%)
01	170,000	135,547	34,453	20.3%
02	**159,000**	**103,683**	**55,317**	34.8%
03	182,644	132,790	49,854	27.3%
04	167,000	142,179	24,821	14.9%
05	152,000	116,742	35,258	23.2%
06	157,000	125,123	31,877	20.3%
			μ	21.2%
			σ	4.1%

The routine losses were relatively similar in five of the six cages at the Hringsdalur site (Table 3.4) and comparable to the losses at Steinanes (Table 3.3). The average loss in those five cages was 21.2% and the standard deviation was 4.1%. In the average loss calculation, cage 2 was left out as it seems to be an outlier, most likely due to a high number of escapees. Potential escape events were reported for cages 2 and 6. However, the fish loss from unit 6 did not stick out from the other cages and it was assumed that no fish had escaped from that cage. It was thus assumed that all the escapees from the Hringsdalur site came from unit nr. 2. The number of escapees from this unit was roughly calculated by subtracting the estimated routine loss from the total loss. The routine loss for cage 2 was conservatively estimated as a 2-Sigma event (95% probability) assuming a normal distribution of routine mortality across cages and calculated as $\mu + 2\sigma = 21.2 + 2(4.1) = 29.4\%$. The number of escapees was thus estimated as Total loss - Routine loss = 34.8 - 29.4 = 5.4%. This calculation suggests with 95% likelihood, that more than 8,500 fish escaped from this cage (159,000 × 5.4% = 8,600 fish).

It was not possible to perform a similar analysis for the site Laugardalur, where the other two events occurred, due to transport of fish between pens and uncertainties in mortality. By assuming the same return rate from both events, the number of escapees from the Laugardalur site can be indirectly estimated from the number of fish entering rivers from each site. Since three escapees were traced to Laugardalur, compared to 12 from Hringsdalur, it was assumed that 2,150 fish had escaped from the Laugardalur site (=8,600/4). The total number of escapees was therefore estimated to be in the close to 11thousand fish, of which 15 were caught in rivers. Assuming a 50% fishing efficiency gives a total number of around 30 late escapees and thus a return ratio of 0.27% (100 × 30/11,000).

The reported production in the area, from Icelandic ocean-based salmon farms in the year 2018, was around 13,500 tonnes. Based on an estimated number of 11 thousand escapees, as explained above, the escape coefficient (*S*) is therefore calculated as 0.81 escapees per tonne produced. A reference value for Norway, based on long-term Norwegian data is calculated as 0.86 escapees per tonnes produced (Table 2.3).

3.1.4 Distribution of the escapees

All the escapees 2018 were late escapees. To predict the distribution of late escapees, the Weibull variables β = 2.0 and η = 1000 were used in the distribution model, which produces a positively skewed distribution (clockwise) from the point of escape and distributes 67% of the fish within a distance of 1000 km from the point of escape. A fitting of the observed late escapee distribution in 2018 required the coefficients β = 1.5 and η = 540, or a somewhat narrower distribution than originally predicted by the model (Fig. 3.1).

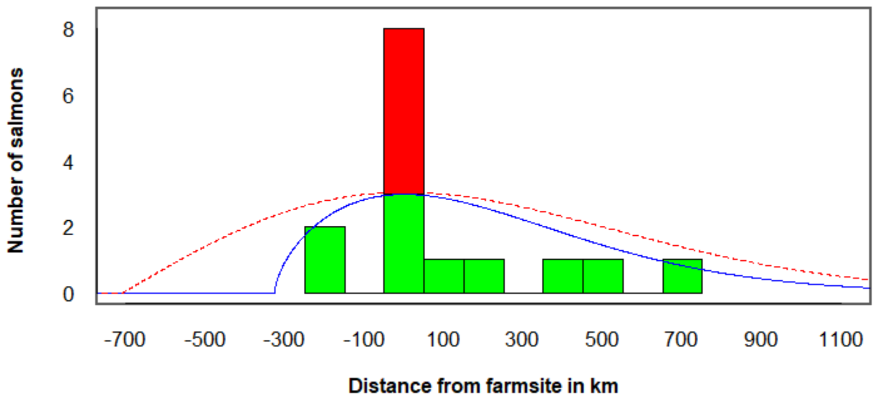


Figure 3.1 The distribution of late escapees from the year 2018. Bars show the number of fish caught and the x-axis shows the distance from the point of escape. Two Weibull functions are shown with coefficients

β = 1.5 and η = 540 (blue line) and β = 2 and η = 1000 (red dashed line). A positive distance shows a clockwise migration.

The observed late escapee distribution in 2018 indicates that late escapees may have a narrower distribution than originally projected in the risk assessment (Fig. 3.1). The actual numbers of caught escapees are low but they provide some preliminary support to the approach used in the risk assessment. They also suggest that the Weibull function is useful for estimating the distribution probability for late escapees and that the first estimate of the coefficients was not far off.

All fish caught in the summer of 2019 in Mjólká, Arnarfjordur originate from the escape event in Hringsdalur in Arnarfjordur in February 2018 (Figure 3.1 red column). As a result, these fish have stayed and survived in the sea for a longer period than was expected in a previous risk assessment. The 5 fish caught in 2019 in Mjólká were all close to the farm sites, as Mjólká is 26 kilometres from Hringsdalur and 16 kilometres from the Tjaldanes farm site in Arnarfjördur. It is likely that they have stayed close to the net-pens during winter and fed on pellets from the pens.

All fish caught in the summer of 2019 in Mjólká, Arnarfjordur originate from escapes from the escape event in Hringsdalur in Arnarfjordur in February 2018 (Figure 3.1 red column). As a result, these fish have stayed and survived in the sea for a longer period than was expected in a previous risk assessment. The five fish caught in 2019 in Mjólká were all close to the farm sites, as Mjólká is 26 kilometres from Hringsdalur and 16 kilometres from the Tjaldanes farm site in Arnarfjördur. It is likely that they have stayed close to the net-pens during winter and fed on pellets from the pens.

In Norway, the timing of escape has been estimated by analysing the fatty acid profiles of the escapees, since the profiles are different after feeding on fish feed versus a wild diet. Based on such measurements it has been concluded that most escapees entering Norwegian rivers did escape from farms during the same year (Glover et al. 2019). The Icelandic results, which are based on genetic tracing of origin, may however indicate that this methodology may be misleading. These recent results indicate that some late escapees can stay close to cages into the for more than one year and feed on pellets from the cages. They can therefore not be distinguished from recent escapees based on their and their fatty acid profiles. This hypothesis will be confirmed through the planned fatty acid analysis of samples from the Mjólká escapees from 2019.

3.1.5 Return of post-smolts as a function of size

The Institute of Marine Research in Norway conducted a series of simulated escapes of farmed Atlantic salmon from seawater net-pens in the years 2005-2008. Individually tagged post-smolts and adult Atlantic salmon were released from various locations at different times of the year (Skilbrei et al., 2015). Post-smolts that escaped during their first summer were capable of rapid migration towards the open sea. A fraction returned to spawn and was recaptured after 1–3 years at sea. In this report, we have extracted data from this paper for further analysis. The numbers of fish recaptured in rivers (1–3 years) decline with average size at release (50 - 1900 g). It is assumed that the fishing efficiency was 100%, i.e. that all the returning escapees were recaptured. The total number of post-smolts released in the experiments was 61,344 fish.

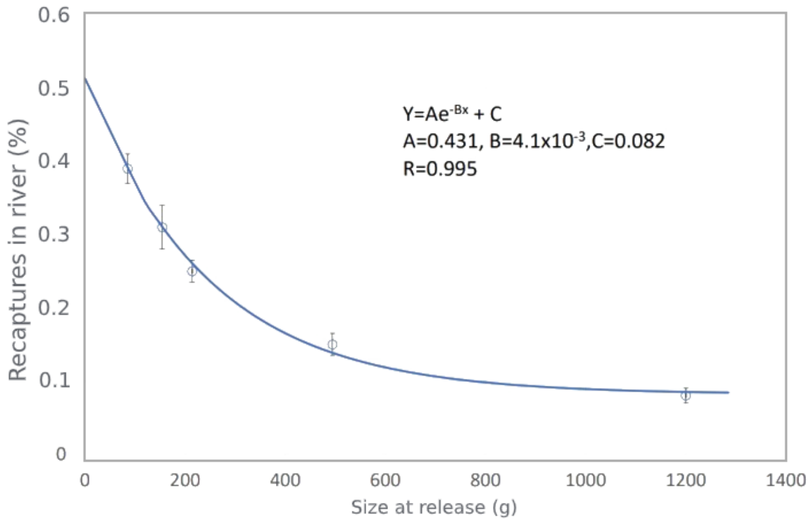


Figure 3.2 Recapture of post-smolts in rivers after 1-3 winters at sea as a function of release size. Error bars show the standard deviation of recapture for each size class. The post-smolts were divided into groups of 50-120 g (x = 85 g; 20,178 fish), 140-160 g (x = 154 g; 19,487 fish), 190-240 g (x = 214 g; 17,506 fish), 430-580 g (x = 494 g; 7,309 fish) and 950-2000 g (x = 1,200 g ; 4,163 fish).

The relationship between release size and recapture can be described with an exponential decay function, until a lower limit plateau of 0.08% recapture is reached at a release size of about 1000 g (Fig. 3.2). Based on the above function, a 200 g escapee has a 28% less chance of recapture than a 93 g escapee, the average smolt stocking size in Norway (Table 3.4). Similarly, a 500 g escapee is predicted to have a 64% less chance of recapture. These examples clearly show the potential of stocking larger smolts to mitigate the number of early escapees returning into rivers.

Table 3.5 Predicted relative recapture of large smolts compared to the predicted recapture of 93 g smolt escapees, based on the function presented in Fig. 3.2

Smolt size (g)	Relative recapture (%)
93	100
200	72
250	63
300	55
350	49
400	44

450	40
500	36

3.1.6 Recent Norwegian findings on late escapees.

Since 2014, five Norwegian research institutions, through an extensive collaborative network, have implemented a monitoring programme that has reported the intrusion of farmed escapees in ~200 rivers annually. The monitoring program publishes an annual report on escaped salmon every year (Aronson et al. 2019). According to the report, the average number of escapees during the last 10 years is about 188 thousand fish per year. The number of reported escapees is highly variable between years, but the variation is, however, not reflected in the Norwegian recapture statistics. It is concluded in the report that the real number of escapees is probably much higher than that.

In Norway, farmed escapees cannot be reliably traced to farming sites as in Iceland, because regulations on genetic samples from parent fish are not in place. Estimates of farmed escapee intrusion into Norwegian rivers are primarily obtained from the following four sampling methods: summer angling surveys (verification by scale reading), autumn pre-spawning angling surveys (verification by scale reading), autumn pre-spawning brood stock collection for local supportive breeding programmes (verification by scale reading) and autumn pre-spawning snorkelling surveys (visual identification with some removal and subsequent verification by scale reading (Glover et al. 2019)).

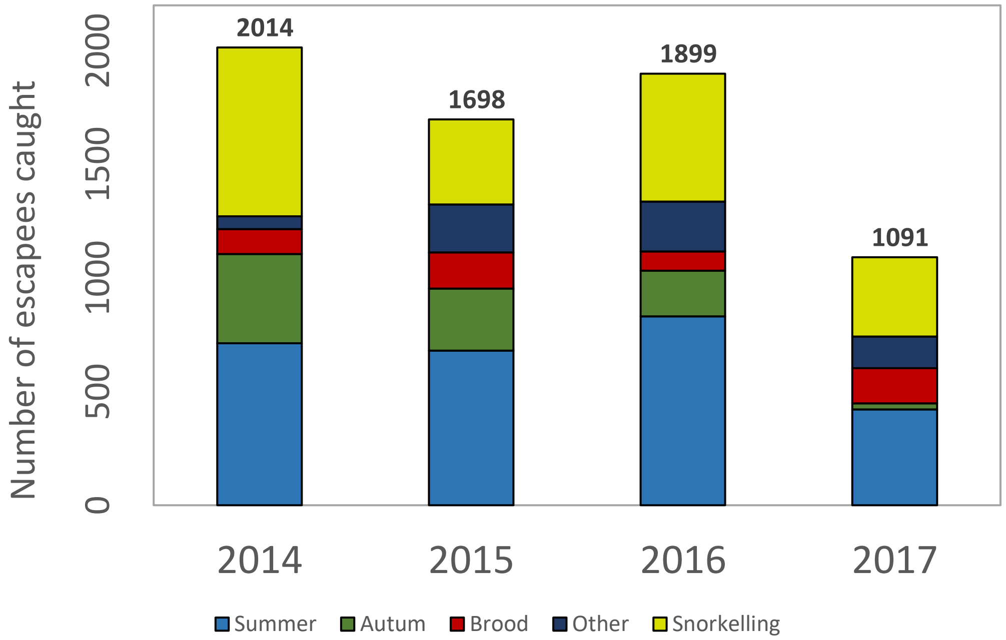


Figure 3.3 The total number of escapee recapture in Norway during the years 2014 – 2017, sorted by sampling method. From Glover et al.2019.

Based on the official average number of salmon escapees from Norwegian farms (188,000 per year) and an average of 1,700 farmed salmon caught in rivers each year (years 2014-2017), the ratio of escapees captured in rivers is 0,9%. The fishing efficiency of angling is probably higher in Iceland (50%) than in Norway due to the clarity of water and other factors. Snorkelling surveys may identify 60-70% of all farmed escapees but the error of this method is unknown (Svenning et al., 2015). With all methods added we assume that the overall fishing efficiency is the same in both countries, 50%. The river migration rate in Norway is therefore assumed to equal two-fold recapture rate or 1.8%.

If the total number of returning escapees is known, a migration factor can be calculated in relation to the total national production level. We have defined such a factor, which we choose to call the *Migration Rate of Escapees* (MRE), expressed as twice the number of escapees captured per 1000 ton produced. The calculated MRE values for the year 2018 are 2.6 for Norway (1,700 escapees / 1.3 million tonnes × 2) and 2.2 for Iceland (15 escapees / 13.500 tonnes × 2), which is an identical number considering the error in the estimate.

In the Norwegian National Monitoring Program (Aronson et al. 2019) no attempt is made to trace the origin of the escapees and therefore the relative recapture from individual escape events is not stated. Therefore, to obtain some reference values about recapture rates, we studied published reports about the number of late escapees captured in rivers from individual escape events. Since genetic data is not available for farmed salmon in Norway, the tracing of origin in these studies is based on scale reading and a comparison of fish size with size distribution in the pens. Extraction of information from these reports (years

2016 and 2018) on catches of late escapees in Norwegian rivers gives a somewhat broad picture of the returns of farmed escapees to rivers (Hellen et al., 2017; Aronsen et al., 2019a,b; Kanstad-Hanssen et al., 2017; Kambestad et al., 2017). The recapture ratio is calculated as: number of escapees caught in rivers / (number of escapees - fish caught at sea) × 100. Only fish from a particular event are included (Table 3.7).

Table 3.7. Summary of results from six reports on escape events in Norway in the years 2016 and 2018.

Locality	Date	Number of esc.	Captured in rivers	Captured %
Bergdalen	24.5.2016	30,180	252	0.83%
Kvitfloget	8.7.2016	5,368	11	0.20%
Skonseng	9.9.2016	6,358	384	6.04%
Oterstegdalen	1.2.2018	8,320	208	2.50%
Geit and Aust	15.2.2018	106,700	82	0.08%
Frohavet	3.9.2018	5,887	36	0.23%
		172,813	973	0.56%

The average recapture ratio in these events, based on the estimated number of escapees, was 0.56% but with a wide variation between events. Due to the high relative magnitude, the events in Geitryggen and Austvika have a significant impact on the average, and if omitted, the average rises to 1.35%. The report states that the return of escapees from this specific event was probably underestimated due to low water levels and absence of snorkelling in rivers. No correlation was found between factors such as time of year or the size of event. The average size of the escapees was not indicated in the reports. Some reports had a very wide size range, such as 1-7 kg in the report from Bergdalen (Hellen et al., 2017) but all were regarded as late escapees. It was difficult for these authors to trace the fish origin to specific escape events, since DNA data was not available. Overall, these recapture ratios are in good agreement with the average recapture ratio from the National Monitoring Program (0.9%).

From the beginning of the monitoring program in Iceland in the year 2018, one escape event can be presented and analysed in the same way (see below). The difference is that each escapee can be traced more accurately to the site of escape, using genetic methods. The basis for this possibility is a provision in the Regulation on aquaculture, which stipulates the obligation to use genetic markers to enable tracing of salmon escapees to certain aquaculture sites (Reglugerd um Fiskeldi 1170/2015 article 49[1]).

Locality	Date	Number of esc.	Captured in rivers	Recapture (%)
Hringsdalur	11.2.2018	8.679	12	0.14%

In Iceland, the total migration ratio (L_G) can be expected to be twice the recapture ratio or

[1] In addition, salmon roe producers are obligated to preserve genetic material from farmed salmon, so that it is possible at any time to trace the origin of farmed salmonids that escape from cages and captured later. Data and biological samples of farmed fish shall be sent to the Marine and Freshwater Research Institute.

0.28% (50% fishing efficiency).

3.1.7. Studies of genetic introgression using electrofishing.

In the study of Gudmundsson et al. (2017), DNA was sampled from fingerlings from 16 rivers during the periods August 2015 and August / October 2016. An allele frequency study of 14 microsatellite markers was performed using the computer program STRUCTURE 2.3.3 (Pritchard et al., 2000). The results of this study provide evidence that farmed salmon escapees of Norwegian origin (SAGA stock) have spawned in aggregation with wild salmon in rivers close to the net-pens. A clear indication of genetic introgression could be seen in wild salmon from Botnsá river in Tálknafjördur and Sunndalsá river in Trostansfjördur, which is one of Arnarfjördur's inner fjords. In the Botnsá river, four hybrids (WF) and two all-farmed (FF) juveniles were found, all belonging to the 2014 cohort. The sampling is limited, but it seems that half of the analysed juveniles from the river Botnsá was of farmed origin. The authors explain the hybrids by the fact that farmed salmon have spawned in the river and reproduced with wild salmon (probably farmed females and wild males). The authors postulate that these are the offspring from escapees from an incident in Patreksfjördur in November 2013 (Gudmundsson et al., 2017). The pure FF genotypes were possibly the offspring from two escapees, but it is also possible that they escaped as juveniles from a nearby smolt hatchery.

In Sunndalsá river, situated about 10 km from the net-pen area in Fossfjördur (the southernmost fjord of Arnarfjördur), five juvenile hybrids were detected and all but one belonged to the 2015 year-class. These hybrids were of mixed parentage (WF) and indeed, in 2015, two adult escapees were found at the dam Mjólkárvirkjun in Borgarfjördur (the northernmost interior fjord of Arnarfjördur), thus confirming the existence of escapees in the area at the time. In Sunndalsá genetic introgression was confirmed in all juvenile salmon collected in the period 2011-2015. Very few escape events were reported during this period and this raises the question whether a minor leakage of escapees may have occurred every year during this period. It was concluded that there are strong indications that genetic introgression has occurred in these rivers.

However, the introgression was only detected in rivers closest to the farming areas and these rivers contain very few wild salmon. There is still some uncertainty regarding the analysis and interpretation of the results. Overall, signs of introgression were detected in six rivers (Table 3.6).

Table 3.8. Hybrid (WF) and all farmed (FF) fingerlings electrofished in the years 2015 and 2016 in six Icelandic rivers (Gudmundsson et al., 2017).

River (location)	No. of WF	No. of FF
Botnsá (Arnarfjördur)	5	2
Selárdalsá (Arnarfjördur)	1	
Sunndalsá (Arnarfjördur)	5	
Sandsá (Önundarfjördur)	1	
Mjólká (Arnarfjördur)	7	
Bjarnardalsá (Önundarfjördur)	1	
Total	20	2

4. Discussion

In this report, we present a model-based approach for assessing the potential intrusion of farmed Atlantic salmon escaping from net-pens in predefined farming areas in Iceland. We present a model for the predicted number and distribution of farmed escapees entering Icelandic fishing rivers.

In the original version of the model, the model parameters were based on available data from the literature. In this report, we present the results from two years (2018 and 2019) of monitoring farmed escapees in Icelandic rivers. We adjust the model variables based on empirical data from the genetic tracing of captured escapees, as well as calculations to estimate the size of reported escape events. All escapees during the two years of monitoring came from three escape events in 2018. In all cases, the escapees were so-called late escapees. Two other events were reported in 2019 with post-smolts escaping, which are not expected to return until 2020 or later, after one or more winters at sea. Therefore, the monitoring thus far has only produced data on late escapees and no data on smolts and post-smolts have been obtained.

Below is a discussion about the parameters used in the Icelandic risk assessment model, with a comparison of the initial and updated values.

4.1 Evaluation of the Escape coefficient (*S*)

In the initial model, the Escape coefficient (S) was based on the total yearly production of salmon. The results from the model were also presented in terms of recommended maximum yearly production numbers for each fjord, assuming a 1:1 ratio between yearly production and maximum biomass. However, new information indicates that this ratio may typically be close to 0.8:1 for Icelandic salmon farming, i.e. the yearly production level is only about 80% of the maximum biomass. Furthermore, the Carrying capacity for open cage farming has previously been assessed by the MFRI in terms of maximum allowable biomass for each fjord. Therefore, a fjord with a carrying capacity of 10,000 tonnes (maximum biomass) will only be able to sustain a yearly production of 8,000 tonnes, or even less in areas with lower biomass turnover. A lower biomass turnover also means that the total recommended production of fertile farmed salmon from the initial model (71,000 tonnes per year) is retroactively reduced to 57,000 tonnes. It must be emphasized that the production levels in Iceland are still nowhere near these threshold values, as the production was close to 30,000 tonnes in the year 2020.

In view of the above, the Risk assessment model has now been changed so it will be directly comparable to the calculated and approved carrying capacity of each fjord. In the updated version of the model, the Escape coefficient (S) is based on the maximum biomass of salmon and the results are presented in terms of recommended maximum biomass.

In the initial Risk assessment model, the Escape coefficient ($S = S_G + S_S$) was 0.8 escapees per tonne produced per year. After adopting the new 0.8:1 ratio this initial value thus equals 0.64 escapees per tonne of maximum biomass per year.

In the present re-evaluation, the Escape coefficient (S) remains unchanged as 0.8 escapees per tonne produced in the current re-evaluation, equivalent to 0.64 escapees per tonne of maximum biomass per year. This decision is based on the results from the monitoring program as outlined in this report. The analysis of reported escape events produces an average Escape coefficient of 0.81 escapees per tonne produced. No data is yet available about the return of early escapees in Iceland and a 50:50 split between early and late escapes is therefore still used, as in the previous assessment.

4.2 Parameters of distribution functions for late and early escapees

The distribution range of the late escapees seems to be somewhat narrower than assumed in the original model. The value of the η parameter was initially estimated η = 1000 but a value of η = 540 appears to give a better fit to the observed distribution of late escapees. The distribution of late escapees is also more positively skewed (clockwise with the coastal current) with β = 1.5 instead of the β = 2.0 original estimate. It was also apparent that some of the late escapees stayed resident close to the event site for over a year, probably feeding on feed pellets from the sites.

No data is currently available for the distribution range of early escapees and the parameters for distribution of early escapees were therefore kept unchanged.

4.3 Evaluation of post smolt (early escapees) return to rivers (*L_S*)

No data on the return of smolt- and post-smolt escapees have been obtained so far in the Icelandic monitoring program. However, by analysing published data from Norwegian escape simulations (Skilbrei et al., 2015) some more information on post-smolt escape migrations can be obtained beyond our initial assumptions. It seems that the recapture of released farmed fish decreases with increasing size at release, according to an exponential decay function. According to this function, the predicted recapture percentage of 100 g early escapees is around 0.4% and, assuming a 50% fishing efficiency in rivers, the return rate (L_S) can be estimated as 0.8%. According to the exponential function, a 350 g escapee is predicted to have 50% less chance of recapture than a 93 g escapee.

As already described, the model calculations account for *''homing''* (where early escapees return to the site of escape and do not attempt river migration), which decreases the calculated return rate nonlinearly depending on distance from river. In effect the calculated return rate the model is much lower than L_S. See Figure 2.3 for clarification.

4.4 Evaluation of late escapees return rate to rivers rate (L_G)

The late escapee return ratio in the original assessment model was cautiously estimated as 3.3%. This value was based on the assumptions of 15% acquired sexual maturation (M) of late escapees and a 22% relative risk time. The late escapee return ratio was therefore calculated as: $M \times R/T = 0.15 \times 0.22 = 0.033$ or 3.3%. This initial value can be compared to the analysis of the Norwegian escape reports (Table 3.7). According to those results and with the assumption that return rate equals 2 × recapture rate, the average return to rivers (L_G) was 1.12%, with a high variance or 1.2%. Numbers from the Norwegian National Monitoring Programme yield the ratio of escapees captured in rivers as 0.9%, and thus an average return rate (L) of 1.8%. The numbers from the National Monitoring Programme are a sum of both early and late escapees and do not account for the reduction in return due to sea fishing. In view of the Norwegian statistics for recapture of escapees in rivers, the initial value of the late migration rate in the model (3.3%) was a reasonable first estimate when considering the precautionary rule.

However, after the first two years of monitoring in Icelandic rivers, the return of late escapees appears to be much lower than predicted in the original model. The estimated return rate (L_G) from the Hringsdalur escape event was only 0.26%. This value is based on an indirect calculation of the number of escapees from the event and could possibly be underestimated. In comparison, the average return rate extracted from Norwegian escape reports is estimated as 0.56% - 1.35% (Table 3.7). In the present re-evaluation the return rate of late escapees is revised and lowered to 1.1%. The revised value of the parameter is thus based on a reasonable compromise between the results of the monitoring program and Norwegian escape reports. The escape coefficient (S) is, however, not changed in the revision.

4.5 Comparison between Iceland and Norway

The end result of the risk assessment model is the actual number of returning mature escapees that are predicted to enter salmon rivers to spawn. Expressing this value in relation to the yearly production level gives the Migration Rate of Escapees (MRE). The values of MRE for Iceland and Norway are estimated as 2.2 vs. 2.6 fish per 1000 tonnes produced, respectively. Net-pens in both countries, are designed in accordance with NS 9415 (Norwegian Standard 9415 for pen farming equipment to prevent fish escapes). The weather conditions are harsher in Iceland and more escapees could be expected on that basis. As a precaution, the revised model now assumes an average MRE of 4.3 for Icelandic salmon farming.

It is, however, important to explain that a high MRE does not necessarily mean that many escapees will migrate to major angling rivers. When looking at the escape events in the Icelandic monitoring program, it seems that many of the late escapees (8 out of 15) turn up close to the farming site. These rivers are small and migrated by a very limited number of wild salmon. It appears that a proportion of grow-out (late) escapees can remain close to pens and feed on pellets falling through the nets (Fig. 3.1). Four of the recaptured escapees had escaped one and a half year earlier and they thus seem to be able to survive in the wild for prolonged periods. For example, fish no. F181304 (See Table 3.2) which was caught in Mjólká in the summer of 2018, did not match with any possible parents from year classes 2014-2016 and was probably from an older parent year class.

Due to restrictions, salmon farming in Iceland is prohibited in the areas close to the major salmon angling rivers (Fig 2.2). In effect, the open-cage farming of salmon (and other salmonids) is only possible on the West Fjords and the East Fjords, where salmon rivers are few and the majority of angling rivers are located far from the farming areas. Only a minority of the late escapees predicted by the model can thus be expected to migrate to the major angling rivers due to the large distances between salmon rivers and farming areas. Under the current spatial restrictions for salmon farming in Iceland, there are only three angling rivers which are located close to farming areas and thus fall into the high-risk category of possible intrusion and introgression from salmon farming. These rivers are absolutely dominant for the outcome of the risk assessment model.

4.6 Revision of risk assessment coefficients based on monitoring results

The following changes are made to the risk assessment coefficients:

Coefficient		Former value	New value	Change Y/N
Early escapees				
Homing coefficient. (H):		0.25	0.25	N
Weibull coefficients:				
	β =	2.5	2.5	N
	η =	170	170	N
Return rate (L_S):		1.85%	1.30%	Y
Late escapees:				
Weibull coefficients:				
	β =	2	1.5	Y
	η =	1000	540	Y
Return rate (L_G):		3.3%	1.1%	Y
Escape rate: (E)		0.8	0.8	N
Late/early escapees:		50/50	50/50	N

4.7 Monitoring and Preventive measures

Present results show clearly the importance of sufficient spatial distance between farming area and salmon rivers. In Ísafjardardjúp two angling rivers are situated at the head of the fjord. Therefore, we advise that the farming area should be restricted to areas west of the line between Ædey and Ögurnes.

Riverwatcher fish counters have been installed in both salmon rivers in Ísafjardardjúp (Langadalsá and Laugadalsá). The systems are connected to a web-based program displaying live images on our webpage. This web page is open for the general public and examined by our staff daily. This can be connected to a remotely controlled fish trap. It is planned to set up a

Riverwatcher in Breiddalsá, on the East fjords, the closest river to the farming areas in that district. It is planned to be in operation in spring 2021.

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4.10 Supplementary data

Revised Risks Assessment URL: https://ahaettumat.shinyapps.io/Hafro2020/

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