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Causal analysis of escape of Atlantic salmon and rainbow trout from Norwegian fish farms during 2010–2018

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ABSTRACT

Farmed fish escaping into the wild and other environmental concerns have curbed the expansion of the Norwegian aquaculture industry. Detailed knowledge of both direct and underlying causes of previous escape episodes is crucial to ensure successful development of new technology and targeted safety-measures at fish farms. This paper provides detailed descriptions of both technological, human and organisational factors relevant to escape of fish from Norwegian fish farms during 2010–2018.

Fish farmers in Norway are obliged by law to report escape incidents to the Norwegian Directorate of Fisheries. A total of 305 reported escape incidents with Atlantic salmon (*Salmo salar*) or rainbow trout (*Oncorhynchus mykiss*) were confirmed from 2010 to 2018, involving in total 1.960.000 registered escapees.

Analysis of 298 of these incidents shows that most registered escapees came from sea-based fish farms (92%), while 7% were from land-based facilities and 1% from transportation between sites. Most escape incidents were directly caused by technological factors, with holes in the net as the most common cause of escape. Bad weather or handling of weights and net prior to delousing have been associated with increased probability of escape incidents.

In addition to direct and contributing causes, mostly technological, escape incidents may also have underlying causes related to human and organisational factors. These causes may have triggered the incidents or prevented barriers from being effective, with technical damage and escape of fish as result. Relevant human and organisational causes were explored through interviews with employees that have experienced escape incidents.

1. Introduction

Atlantic salmon (*Salmo salar)* and rainbow trout (*Oncorhynchus mykiss*) are the primary species for fish farming in Norway. In 2018, 1.28 million metric tons of farmed salmon and 68 thousand tons of rainbow trout were slaughtered (Statistics Norway, 2020). The Norwegian aquaculture industry is a profitable global exporter, and production numbers have increased considerably since the early days of fish farming in the 1970s. However, in recent years the industry's ambitions for further growth have been curbed by environmental concerns. Problems with parasites and farmed fish escaping into the wild led to a stagnation in produced biomass between 2013 and 2016 (Norwegian Directorate of Fisheries, 2020a). During 2017–2019, an alleged environmentally sustainable increased production was allowed in areas given a “green light” (Norwegian Ministry of Trade, Industry and Fisheries, 2015a).

The major concern with escape of farmed salmon is that it may pose a threat to wild salmon due to interbreeding. Escaped farmed salmon and salmon lice from fish farms have been identified as expanding population threats (Bolstad et al., 2017; Forseth et al., 2017; Glover et al., 2017). Escape may also lead to loss of income, and heavy fines for the fish farmer, and receives high media attention. Fish farmers are required by law to prevent escapes. Escapes that are considered to be the consequence of inattentiveness, or have not been properly restricted through recapture, or have not been properly reported, are considered a crime (Norwegian Ministry of Trade, Industry and Fisheries, 2008; Glover, 2010). The industry is concerned with the opinion of the public, as it may influence access to production sites and acceptance for aquaculture in local communities (Olsen and Osmundsen, 2017).

Most escape incidents are directly caused by failure of technical equipment, and technological causes have often been the focus of investigations by fish farming companies and authorities (Føre and Thorvaldsen, 2017; Jensen et al., 2010; Jackson et al., 2015). Already in 2003, a first version of the technical standard for fish farms, NS9415 (Standards Norway, 2009), was launched and enforced by law through the “NYTEK”-regulation (Norwegian Ministry of Trade, Industry and Fisheries, 2015b) in 2005 as a measure for the predominant technological factors. This led the industry to make technological investments that reduced the number of escapees in the following years (Jensen

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et al., 2010). In recent years, human and organisational factors have been identified as important underlying causes (Thorvaldsen et al., 2015; Thorvaldsen et al., 2018). The awareness of human and organisational factors has increased with the expansion of the industry, the development of larger farms and companies, and more complex operations and organizations.

Detailed knowledge on both direct and underlying causes of previous escape episodes is crucial to ensure successful development of new technology and targeted safety-measures at fish farms. This paper provides detailed descriptions of both technological, human and organisational factors relevant to escape of fish from Norwegian fish farms during 2010–2018. The emphasis is on technological causes, which often are well documented and thus allow for a quantitative analysis. In addition, new knowledge related to relevant human and organisational factors are presented. This knowledge is useful for fish farmers during identification of causes of escape, and during risk assessments, preventative work and training of employees. It is also of value to technology developers and authorities in their efforts to prevent escapes.

1.1. Causes of escape

The Norwegian Directorate of Fisheries (NDF) receives reports from fish farmers when escapes happen, or if escapes are suspected by fish farmers or others. Fish farmers are obligated by law to report escape incidents to NDF through the aquaculture regulation (Norwegian Ministry of Trade, Industry and Fisheries, 2008). In addition, concerns relating to near accidents and potential hazards may also be reported. The actual numbers of escaped salmon from Norwegian fish farms are higher than the reported numbers. Occasionally, farmed fish that cannot be connected to a known escape incident are observed in the wild. During 2005–2011, the number of escaped salmon was estimated to be 2–4 times higher than the numbers reported to the authorities by fish farmers (Skilbrei et al., 2015).

In recent years, the NDF has used general categories in analysis of causes of escape when presenting this data to the public. These categories are: External cause, operational cause, structural cause, inconclusive and irrelevant. A similar categorisation was also presented in a previous study based on reports for the period 2006–2009 (Jensen et al., 2010). These categorized causal analyses have been published to a limited degree but are mainly used in planning of NDF's activities and presented at relevant seminars. For example, in 2015, the NDF found that 42% of the events were due to operational causes and 27% of the events due to external causes. Furthermore, 26% of the incidents were categorized as inconclusive or irrelevant (Norwegian Directorate of Fisheries, 2016). For these latter cases, the most probable cause of escape was often known by the NDF, but “inconclusive” and “irrelevant” causes were not consistent with only one of their established categories (external cause, operational cause, structural cause) or any of their categories respectively.

Human and organisational aspects related to escape of farmed salmon have previously been explored in a qualitative study applying interviews of employees from several companies that had reported escapes during the period 2009–2012 (Thorvaldsen et al., 2015). This study demonstrated that the course of events behind an escape incident may be complex, with several underlying causes including: Physical work environment, workload and work pressure, training, skills and experience, co-operation and communication, and safety management. Technological factors, including the interaction between humans and technology were also discussed: Employees perceived the risk of escape to be highest during operations involving boats, handling of the net and the sinker tube, and treatment of salmon lice.

1.2. Aquaculture technology and regulation

Sea-based farms are the primary production units for on-growing of salmon smolt in Norway. Technology for sea-based fish farming includes the fish farm, auxiliary equipment for production and operation, and various vessels such as barges and boats. Most fish farms consist of three main components: A cage collar, a net cage and a mooring system. Today, most cage collars are constructed using polyethylene (PE) pipes connected by clamps. Their function is to keep the top of the net cage at the water surface, hold auxiliary equipment, and provide a working platform for the employees. The fish is kept in place by the net cage, which most often is made of nylon netting with a reinforcing rope structure. The mooring system is flexible, allowing the fish farm to adapt to large waves. It consists of ropes, chains, buoys and anchors.

Fish farms are equipped with permanent auxiliary equipment such as weights to ensure sufficient net cage volume, a pump or net to collect dead fish, lice skirts to protect against parasites, feeding equipment, shelters for cleaner fish, cameras and lights. In addition, various equipment will be used during operations, such as net cleaners, buoy ropes for crowding of fish, nets for fish handling and tarpaulins for parasite treatment.

Vessels are used for daily production and maintenance, regular net cleaning operations, necessary de-lousing of fish and transport of fish to and from the fish farm. Both small working boats, specialized service vessels and larger well boats are used to perform work at fish farms on a daily or regular basis.

Fish farming in Norway is regulated through aquaculture licenses defined through the Aquaculture Act (Norwegian Directorate of Fisheries, 2005), that are highly valuable and sought after. In recent years, the Directorate of Fisheries introduced special “development licenses” in order to facilitate development of new fish farming technology that may contribute to solve some of the environmental challenges of fish farming (Norwegian Directorate of Fisheries, 2020b). Through these licenses, authorities called for considerable innovations and unique concepts, rather than improvements or standardization of existing solutions. The aim was to prevent escape, reduce the prevalence of sea lice and enable access to new sea-based production sites.

Over the years technological causes related to main components, auxiliary equipment and vessels have led to escapes. New types of fish farms will be introduced in the years to come, many motivated by development licenses. Most new fish farming technology will have new main components, for instance inspired by oil platforms and ships, and new types of auxiliary equipment and vessels for operations. The new farms may pose new technological challenges related to escapes that are still unknown.

1.3. Objective

This paper provides new knowledge on causes of escapes from Norwegian fish farms during 2010–2018. No studies based on escape reports have been conducted since 2009. The findings presented here adds details on technical causes and identifies relevant human and organisational causes that are valuable for preventative efforts. The objective of this paper is three-fold: First, numbers of escapes in the period 2010–2018, including developments and trends, are presented and discussed. Second, direct and contributing technological causes of escape are described and discussed. Third, underlying human and organisational factors related to previous escape incidents are presented.

2. Materials and methods

The causal analyses presented in this paper are based on data from the Norwegian Directorate of Fisheries, reports from fish farmers and the public, and interviews. Most escape reports are sent by fish farmers, but occasionally observations of farmed fish in the wild are reported by the public. The latter reports did naturally not include any information on causes of escape. All reports of escaped fish during 2010–2018 as well as documentation from NDF's inspections post escapes were acquired for analysis. This data is not available for the public, but the authors were given access for research purposes. In many cases, except for incidents involving low numbers of escaped fish, the NDF will inspect the farm and make a report describing the incident and relevant information. NDF keep a database with relevant information for all reported incidents. This database will most often include a description of the most probable cause of escape based on information from the fish farmer and their own or external expert assessments. In addition, it gives various estimations of the number of escapees, including the fish farmer's initial and updated reported estimates and occasionally an estimate made by NDF. The final estimate by NDF, i.e. the registered number, is based on these estimates and often counting of the fish left in the cage after an escape event. When "escaped fish" is referred to in this paper, this equals "registered escaped Atlantic salmon and rainbow trout from Norwegian fish farms". Finding the exact number of escaped fish during an escape incident is often difficult, if not impossible (see 4. Data quality). Thus, the registered number must be considered as an estimate.

During the period of 2010–2018, 514 reports of escapes, concerns or escape hazards were registered by the NDF (Norwegian Directorate of Fisheries, 2019). There is a two-step reporting system, where the first report must be filed immediately after suspicion of possible escape of fish, the second when more detailed information is available. A total of 269 reports did not conclude with any escaped fish.

The presented analyses include incidents involving Atlantic salmon and rainbow trout. Compared to salmon and rainbow trout, production of other species for consumption, including Atlantic cod (*Gadus morhua*) and Atlantic halibut (*Hippoglossus hippoglossus*), is very limited. In addition, associated production technology and methods, and behavioural features affecting escapes may not be comparable to salmon and rainbow trout (Moe et al., 2007; Moe et al., 2009). Therefore, 27 reports involving other species (mostly cod) were not included in the analysis. This left 305 confirmed escape incidents with salmon and rainbow trout (hereafter referred to as *fish*) over the 9-year period. The causal analysis in this paper is based on 298 of these incidents. This is seven incidents less than reported by NDF in May 2019 (Norwegian Directorate of Fisheries, 2019). This is because the numbers have been updated after the causal analysis was performed. The seven additional incidents involve a small number of escaped fish and would not affect the findings in the causal analysis.

The documentation related to each of the 298 relevant incidents was analysed and processed to provide an overview of the causes of escape. The aim was to produce causal categories that can be used to identify critical risk factors and to implement targeted measures at fish farms to prevent future escapes. It was sought to keep as much detail as practically possible and use an unacademic language, to provide categories that are meaningful and applicable for all employees at fish farming companies. Both human, technological, and organisational factors were sought after in the documents. Overall, there was little information to be found regarding the human and organisational factors. It should be noted that fish farmers are not required to address these factors, and reports focus on technical causes. It was thus concluded that this dataset was consistent for technological factors only.

A bottom-up approach was applied: Direct and contributing, mainly technical causes of escape were found for all incidents, and suitable causal categories were established based on this data set. The direct cause of escape was identified as the failure mode of the main function of the technology (*How did the main function fail?*); the main function in this context is preventing escape of fish. In addition to determining the direct cause, contributing causes (*Why did the main function fail?*) was identified. In cases where the cause of escape was disputable, the cause considered most likely or most influential was chosen by the authors. In some cases, mostly involving small escape numbers, there was not enough information available to establish a probable cause of escape and the cause was given as "inconclusive".

To study the number of registered escaped salmon relative to the total number of farmed salmon for each year, average number of farmed salmon in sea-based fish farms was found for each year. The yearly average number of farmed salmon from 2005 to 2019 was calculated using monthly biomass data available to the public at the NDF website (Norwegian Directorate of Fisheries, 2020a). Trends are indicated using 5-year average values, as escape numbers vary from year to year, often affected by single large incidents. The 5-year average value for a specific year was found by adding the number of escaped fish for the four previous years to the yearly value and dividing this number by five.

Circumstances during escapes, such as specific environmental conditions or operations, were identified and categorized for all escape episodes involving at least 500 escaped fish, using the same bottom up approach as for technological causes. For incidents with relatively small escape numbers (involving less than 500 fish), this information was often not documented. In total, the 109 largest incidents out of the confirmed 298 escape incident was analysed to find circumstances during escapes.

Due to the lack of information regarding underlying causes in the reports, human and/or organisational factors were explored through interviews with employees who had experienced escape incidents. Interview participants were found by contacting a selection of companies that had reported escape incidents to the NDF. The company names were available at the NDF website, and the contact info for each company was found on their websites. A total of 17 employees from five companies were interviewed about six incidents that occurred during 2015–2017. Interviews were semi-structured (Bernard, 2006) and based on an interview guide that addressed the escape events. The employees were encouraged to describe what happened, their opinions of possible causes, what could have been done differently and which measures had been implemented. Follow up questions about human and organisational factors were used to provide further details. For instance: How many hours had the employees been working when the escape happened? Was the distribution of responsibility between employees the same as usual that day? In addition to identifying and discussing causes of escapes, employees were asked to talk about possible worries regarding human and organisational factors and escapes. Guidelines from the Data Protection Official for Research (Norwegian Centre for research data) were followed when handling personal data. All participants gave their consent to be interviewed, based on information about the purpose of the interviews and anonymity in all presentations and publications of results.

Compared to the total number of escape incidents analysed based on reports, the number of incidents investigated through interviews was relatively small. Thus, the identified human and organisational causes were not quantified. The interview data was considered sufficient to establish relevant categories for human and organisational factors. In addition, a previous study on human and organisational factors also provided valuable input in this work (Thorvaldsen et al. 2015).

The qualitative data from the interviews was first sorted according to topics or key words, which was used to establish and describe categories for underlying causes of escapes.

3. Results and discussion

3.1. Registered numbers of escaped fish

The registered number of escaped fish from Norwegian fish farms was found for each year from 2001 to 2019 (Norwegian Directorate of Fisheries, 2019), and are given both for salmon and rainbow trout combined and salmon alone in Fig. 1. Escape numbers varied largely from one year to another, and yearly escape numbers were highly dependent on the occurrence of single large incidents (Fig. 2). Thus, trends in escape numbers cannot be assessed based on developments from one year to another, and 5-year average values has been applied to form trend lines as given in Fig. 1. These trend lines indicate a reduction in number of registered escaped fish from an average annual value of

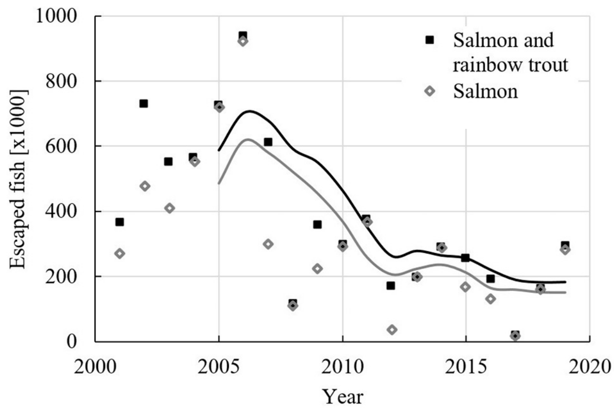

Fig. 1. Number of registered escaped fish per year for 2001–2019. Trend lines based on 5-year average values are given for escape of salmon and rainbow trout combined (black) and salmon only (grey).

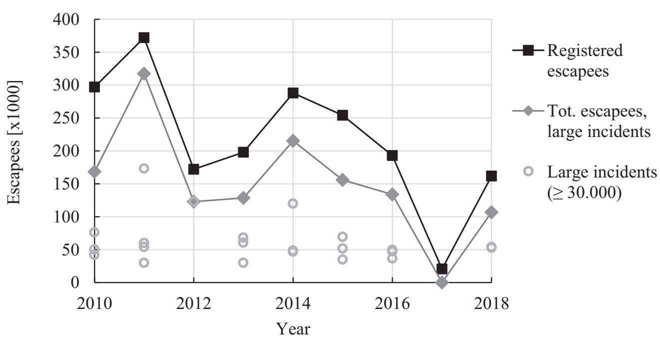

Fig. 2. Number of escaped salmon and rainbow trout registered per year during the period 2010–2018. Large incidents involving 30,000 or more escapees are indicated as grey circles and summed up for each year to give total escapees during large incidents.

700,000 around year 2006 to below 300,000 during 2012–2016. This decline is often credited the introduction of new regulations (Norwegian Ministry of Trade, Industry and Fisheries, 2015b), which were introduced in 2005, requiring that technical standards like NS9415 (Standards Norway, 2009) should be followed by all fish farming companies. Other legislations such as the internal control regulation for aquaculture and the aquaculture regulation, commenced in 2005 and 2008 respectively, are also considered to have had a positive influence on escape numbers (Norwegian Ministry of Trade, Industry and Fisheries, 2004; Norwegian Ministry of Trade, Industry and Fisheries, 2008). Average escape numbers were further reduced to below 200,000 fish during 2017–2019. However, in 2019, 290,000 fish escaped, yielding the highest escape number since 2014. A large fraction of these fish escaped during one large incident where 203,000 fish escaped from a land-based smolt production site. A total of 105,000 of these escapees were recaptured.

During the nine-year period of 2010–2018, which was investigated in this work, a total of 1,960,000 Atlantic salmon and rainbow trout were registered as escaped from Norwegian fish farms. On average, 175,000 salmon and 44,000 rainbow trout were registered escaped per year. During this period, the number of escaped fish varied largely from one year to another, from 20,000 individuals in 2017 to 372,000 in 2011 (Fig. 2). Incidents involving a large number of escaped fish, during for instance harsh weather conditions and farming operations, strongly affected the annual numbers of escapees. Analysis of all incidents involving 30,000 escapees or more, i.e. 30,000–173,000 fish per incident, showed that 22 incidents (7% of 298 confirmed incidents) represented 70% of all escaped fish in this period. Out of these incidents with high escape numbers, at least 9 (41%) were triggered by storms.

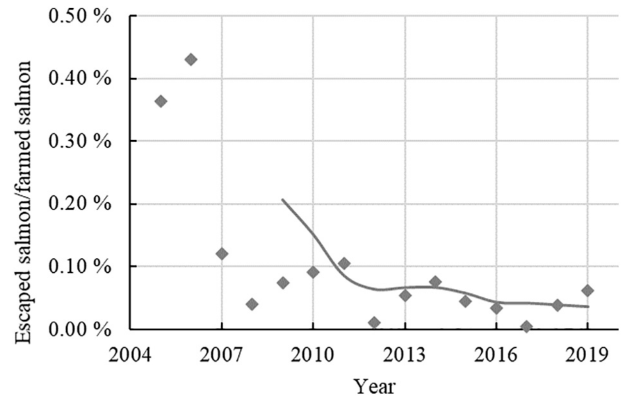

Fig. 3. Number of registered escaped salmon relative to total number of farmed salmon in Norwegian fish farms during 2005–2019, given in percentage. 5-year average values for the time period are given as a smoothed line.

The total number of farmed salmon in Norwegian fish farms has increased from year to year since the start of the salmon farming industry in the 1970s. In comparison, the yearly production numbers of rainbow trout have been relatively stable since 2001. From 2010, the total number of farmed salmon in Norwegian fish farms increased from a yearly average of 319 million individuals up to 380 million during 2014–2016. In recent years, production has increased again, up to 416 million individuals in 2019. Based on these yearly production numbers and the number of escapees, the fraction of escaped salmon was calculated for the period 2005–2019 as given in Fig. 3. A trend line based on 5-year average values is also given in Fig. 3.

From 2008, less than 0.11% of the farmed salmon was registered as escaped each year, and the 5-year average trend line indicate that on average 0.04% of the salmon was registered as escaped during recent years (Fig. 3). In comparison, 0.43% of the salmon was registered as escaped in 2006.

3.2. Causal analysis: technological factors

3.2.1. Direct causes of escape

The analysis of reports of fish escapes during 2010–2018 show that 92% of escaped farmed salmon and rainbow trout escaped from sea-based fish farms, 7% from land-based facilities and 1% during transportation of fish between sites (Fig. 4). Most of these escapees can be related to technological factors as the direct cause of escape.

Considering the total amount of escaped fish, the most important direct causes of escape from sea-based fish farms were holes in the net cage (76% of escaped fish, Fig. 4) and net under water (16% of escaped fish). 'Net under water' includes incidents were the top of the net ended up below the water surface allowing fish to swim out of the cage.

Of 298 escape incidents during 2010–2018, 130 were directly caused by holes in the net, 59 incidents occurred during transportation of fish, 17 incidents occurred at land-based facilities, while 17 were caused by net under water. Thus, considering risk as a product of probability and consequence, the highest risk of escape was escape through holes in nets of sea-based fish farms.

In addition to these direct causes representing 99,95% of the escaped fish (4), there were 55 smaller incidents with other causes, including 51 reported episodes of fish lost during handling of fish at sea-based fish farms. These incidents involved up to 50 fish, and most involved one fish only. Further, there were 17 incidents of unknown origin (cultured fish was observed in sea, but the owner of the fish could not be determined), and one incident at a so-called closed sea-based fish farm.

Escape incidents during transportation and handling of fish have often involved human factors. Among these there are examples of incidents with no evident technological factors. This includes losing fish

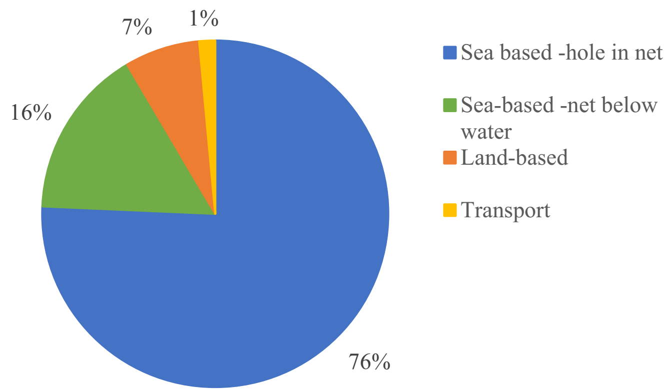

Fig. 4. Direct causes and location of escape of fish given as percentage of the total number of escaped fish in the period 2010–2018. Sea based "hole in net" and "net under water": Fish escaped from sea-based facilities due to hole in net or the top of the net falling below the water surface. "Land-based": Fish escaped due to leakage from tanks at land-based facilities. "Transport": Fish was lost during transport between sites.

during handling (often due to the fish's flight response movements) and accidentally unloading fish outside the cage. It may be argued that technological solutions may have been applied as barriers, not excluding technological factors completely.

3.2.2. Contributing technological causes

Hole in net was the direct cause of 76% of the escaped fish during 2010–2018, and 44% of the escape incidents. In total 1.470.000 fish escaped through holes in nets during 130 incidents in this time period. The technological factors (T) contributing to these incidents are presented in detail in Fig. 5 and Table 1. Analysis of contributing causes show that half of these fish escaped through holes caused by the weight system (T1), and that wear from bottom ring chain and handling of weights were important factors. This includes seven large incidents with 30.000–173.000 escaped fish. Five of these were due to wear from bottom ring chain, one due to handling of weights (during lowering of bottom ring) and one due to wear from weight rope, i.e. the rope connecting the weight to the floater.

Another significant fraction of the holes was caused by conflict with or damage to main components (T2) or auxiliary equipment (T3). The category "Main components" includes conflict with or damage to mooring system, feed barge, cage collar and issues regarding net cage structure (defects) and handling of the net (e.g. reducing net cage volume during crowding of fish). Net cage structure and handling do not represent a large contribution to the number of escaped fish but are relatively frequent. Auxiliary equipment such as dead fish pump and

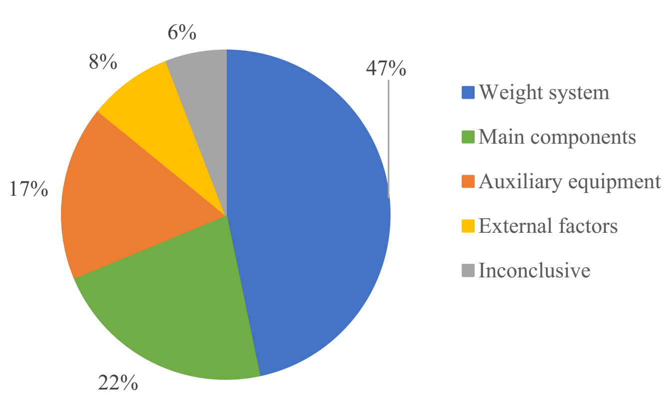

Fig. 5. Fraction of escaped fish and contributing causes to hole in net during 2010–2019. Categories and numbers are presented with further detail in Table 1.

Table 1
Technological factors contributing to escape of fish due to hole in net during 2010–2018. Main categories given in bold.

Technological factors	Number of escaped fish	Fraction of escaped fish[a]	Number of escape incidents
T1) Weight system	**688,000**	**47%**[b]	**28**
Wear from bottom ring chain	351,000	24%	11
Handling of weights	256,000	17%	12
Wear from ropes/ weights	81,000	5%	5
T2) Main components	**324,000**	**22%**[b]	**31**
Mooring	112,000	8%	6
Net cage structure and handling	83,000	6%	20
Cage collar	67,000	5%	4
Feed barge	61,000	4%	1
T3) Auxiliary equipment	**251,000**	**17%**	**25**
Dead fish pump	121,000	8%	8
Various equipment	75,000	5%	13
Net cleaner	55,000	4%	4
T4) External factors	**121,000**	**8%**	**22**
Propeller damage	90,000	6%	9
Predators	19,000	1%	11
Collision and flotsam	13,000	1%	2
Inconclusive	**87,000**	**6%**	**24**

[a] Fraction of total escaped fish due to hole in net.
[b] Due to rounding of numbers, the fractions associated with the subcategories does not necessarily add up to the number given for the main category. Given with decimals, the "weight system" represents the following fractions: 46.73% = 23.84% + 17.39% + 5.498%, while "main component" represents 22,02% = 7,65% + 5,67% + 4,59% + 4,11%.

net cleaners have contributed to holes in nets and escapes, in addition to various equipment including cleaner fish shelter, temporary fish pumps, seines used to collect fish, hoses and feeding equipment. Categories "main components" and "auxiliary equipment" includes nine large incidents with 30.000–76.000 escaped fish. Contributing causes include handling of a dead fish pump, a feed barge that drifted into a cage, conflict with mooring system, a loose net hook falling into the net, unfavourable fastening of a cleaner fish shelter, and net cleaning.

External factors (T4) have caused holes in nets due to conflict with propellers on operating vessels, and bite damage from predators. Propeller damage represents 6% of the fish that escaped through hole in net and has occurred relatively frequently. Predators may create holes hunting for salmon and preying on dead fish. Small sharks called greyfish (*Squalus acanthias*) are a well-known challenge in some areas, and otters (*Lutra lutra*) and whales occasionally create holes in nets.

For several, mostly smaller escape incidents, it has not been possible to come to conclusions about the most likely contributing cause of escape based on the available documentation.

'Net under water' represented 6% of the escape incidents, however the incidents were on average relatively large, representing 16% of the escaped fish during 2010–2018. A total of 70% of the fish that escaped due to net under water, escaped because of conflict with or damage to the cage collar (T2). This includes fires on cage collars and cage collar breakdown due to mooring failure (dragging of anchors). Other technological factors resulting in the top of the net getting under water are handling of the net (T2), insufficient fastening of the net (T2), collisions with vessels and jellyfish clogging the net resulting in the cage being pulled down (T4).

Escape from tanks at land-based facilities has led to farmed fish being released into the sea. Most of the incidents involved open outlets in tanks caused by defect or missing barriers for fish. This includes an incident were 49.000 fish escaped due to an open outlet.

Most of the fish that escaped during transportation was lost during transport from land-based facilities to well boats or from well boats to sea-based fish farms. Technological factors in this context are overflow of grates in well boats, pumping into the sea, holes in hoses, failure in hose couplings, and open valves in well boat.

Fish that escaped during handling were lost in connection with counting of lice, delousing operations, vaccination, health checks and sorting.

3.2.3. Circumstances during escape incidents

Circumstances during escape incidents was investigated for the 109 largest escape incidents, involving 1,943,000 fish, i.e. 99% of the fish escaping during the period 2010–2018. Based on analysis of reports related to these incidents, four main categories for circumstances were identified: C1) Weather and environmental conditions, C2) operations, C3) routine work and maintenance, C4) loading and unloading of fish. Category C2 includes large operations that are assessed not to be a part of routine work (including small and frequent operations) and maintenance. For instance, dead fish removal is categorized as “routine work”, while de-lousing and exchange of nets are categorized as “operations”. Category C3 also includes incidents that was not associated with any specific circumstances. At least 27% of the fish had escaped during bad weather and storms, while 19% of the escaped fish were related to handling of the net cage and weights associated with delousing operations. For 35% of the fish, routine work, maintenance or no specific circumstances were reported. Further identified circumstances were handling of dead fish pump (5% of escaped fish), loading and unloading of fish (4%), cleaning of nets (3%), de-lousing (3%) and strong water currents (1%).

3.3. Causal analysis: human and organisational factors

In addition to technological causes and circumstances, escape incidents often have underlying human and organisational causes. Based on interview data, categories for relevant human and organisational factors were established. These categories reflect descriptions of causes of previous escapes and near-incidents, and concerns expressed by employees.

Three main human factors were identified: H1) Competence and experience, H2) performance ability and H3) communication (Table 2). Lack of competence and experience may be related to new employees, temporary workers, or inadequate training in general. Even experienced workers may not have the competence and knowledge needed for operations that are seldomly performed. Performance ability as a cause of escape is related to workers experiencing fatigue or reduced concentration. Communication issues may be categorized as messages not given or received, and misunderstandings.

Human factors must always be considered in relation to organisational factors. For instance, competence and experience is closely connected with training, and performance ability may be negatively influenced by staffing and working hours.

Five main categories of organisational factors were identified: O1) Planning, O2) training, O3) staffing and working hours, O4) operation and maintenance, and O5) requirements, choices and evaluations (Table 3). Examples of poor resource planning (O1) are lack of competent and experienced personnel, equipment, time to perform the operation safely, and resources such as service vessels and available crew. Other categories related to planning include lacking or insufficient risk assessments and start-up meetings before operations. Distribution of responsibility is also related to planning, making sure everyone knows who does what, what to do in case of changes, delays and emergencies such as escapes.

Table 2
Underlying human factors identified for escape incidents that occurred during 2015–2017.

H1) Competence and experience
Lack of competence or experience
H2) Performance ability
Fatigue
Reduced concentration
H3) Communication
Message not given
Message not received
Misunderstanding

Table 3
Underlying organisational factors identified for escape incidents that occurred during 2015–2017.

O1) Planning
Resources
Start-up meeting
Distribution of responsibility
Delays and changes
Risk assessments
Emergency plan
O2) Training
New operation
New equipment
External actors
O3) Staffing and working hours
Undermanned
Overtime work
Shift work
Long work session/Lack of rest
O4) Operation and maintenance
Work method/work practice
Equipment
Maintenance and inspection
Deviation reporting Procedures
O5) Requirements and choices
Economic priorities
Choice of location for production site
Choice of equipment and work method
Laws and regulations
Certification schemes

Training (O2) is important for newcomers, but also for experienced workers introduced to new operations or new equipment. Insufficient training of external service vessel crews may also be an underlying factor during escape incidents. The category staffing and working hours (O3) includes being undermanned, working overtime or long shifts. This may lead to insufficient rest and in turn affect the performance ability of workers. Operation and maintenance (O4) include methods and work practice, i.e. how the work is performed. It also involves choice of equipment: e.g. new equipment, user-friendliness, and instructions for operating the equipment. Furthermore, lack of maintenance, inspections, deviation reporting and proper procedures may contribute to escape.

Finally, the organisational factors requirements, choices and evaluations (O5) include economic priorities, choice of production site for the fish farms and choice of equipment and work method. Economic priorities may be an underlying cause of escape because it influences other organisational factors. As stated, employees at the fish farms need different resources to perform their work, including proper training, sufficient time to perform operations or maintenance, and equipment. These resources require time and/or financial investments. Furthermore, economic priorities may affect employees both at sea and in on shore management when it comes to having time and/or money to follow up on deviation reports and implementing preventative measures. There are also examples that decisions taken in an early phase (prior to the production phase), have been underlying factors to escape incidents. For instance, choosing sites exposed to harsh winds and currents and or/ choosing equipment (such as nets) that are not compatible with the conditions at the site or the company procedures for operation.

Laws and regulations for aquaculture companies are extensive and require fish farmers to prevent escape, ensure fish health and welfare, and the safety of workers. This means that workers must balance several (sometimes conflicting) objectives in their everyday work. One example of this is the current regime where the acceptable amount of salmon lice is restricted by law and affect the possibilities for increased production of farmed fish. The strong focus on maintaining low levels of salmon lice has led to a higher frequency in de-lousing operations in the industry and de-lousing operations performed during sub-optimal conditions, which in turn could be associated with several reported escape incidents.

Voluntary certification schemes, like the Aquaculture Stewardship Certification (ASC), include requirements that have consequences for equipment and operation. For instance, ASC certified locations may not combine copper based anti-fouling coatings on their nets and on-site high-pressure cleaning and are thus forced to choose between the two. This will probably affect the risk of escape, for instance through need of increased cleaning operations and increased wear of nets. Alternatively, on-site cleaning may be replaced by changing fouled nets with freshly coated nets, an operation that is considered to include a relatively high risk of escape.

Collected reports from fish farmers and NDF mainly described technological factors. When underlying causes was included in the reports, the most common examples were missing or inadequate procedures or risk assessments.

4. Data quality

4.1. Technological factors

The data in the reports from NDF and fish farmers is considered sufficient to give clear indications of the most common and important technological causes. In many cases, thorough investigations have been performed, and there are several reported incidents in many of the causal categories. However, the quantification of escape numbers will be somewhat uncertain: There are sources of error regarding both the number of escaped fish, the number of escape incidents and the causes of escape. Escape numbers are associated with several sources of errors and are in many cases based on estimates. The escaped fish are often impossible to count as they will swim away from the site (Solem et al., 2013). In addition, escape episodes are most often detected during or even after the incident. Often, the escape numbers are based on counting of the remaining fish. Thus, escape numbers will be affected by uncertainties in current biomass numbers, uncertainties in counting technology and uncertainties in the general, daily loss of fish due to for instance mortality. In addition, there are also unregistered escapes of cultured fish, exemplified by observed cultured fish that cannot be linked to a known incident.

4.2. Underlying human and organisational factors

For the human and organisational factors, data have been acquired through interviews related to a limited selection of escape incidents and does thus not allow for quantification. Because fish farmers are not required to report these causes, there is little or no information to be found in the reports. Interview data provides a basis for identifying categories, but there are likely to be other causes for escapes that have not been identified through the methods used. Still, the categories presented in this article provides a starting point for the fish farmers that they can use to fill in other relevant factors. Sometimes the measures needed are not technical, but rather related to the organization of the work. To identify such factors, investigation methods may be useful (Okstad and Tinmannsvik, 2019).

5. Conclusions

During the nine-year period of 2010–2018 a total of 1.960.000 Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*) were registered as escaped from Norwegian fish farms by the Norwegian Directorate of Fisheries. On average 0.04% of the salmon was registered as escaped during recent years.

Analysis show that 92% of the escaped farmed salmon and rainbow trout escaped from sea-based fish farms, 7% from land-based facilities and 1% during transportation of fish between sites. Most of these escapees can be related to technological factors as the direct cause of escape.

Holes in the net was the most important direct cause of escape of fish from Norwegian fish farms during 2010–2018. Analysis of contributing causes show that half of these fish escaped through holes caused by the weight system (T1). Another significant fraction of the holes was caused by conflict with or damage to main components (T2) or auxiliary equipment (T3). Circumstances such as bad weather and storms (C1), and handling of weights and net prior to delousing (C2) increased the probability of escapes.

Escape incidents often have underlying human and organisational causes. Three main human factors were identified: H1) Competence and experience, H2) performance ability and H3) communication. Five main categories of organisational factors were identified: O1) Planning, O2) training, O3) staffing and working hours, O4) operation and maintenance, and O5) requirements, choices and evaluations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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