Aquaculture Reports 31 (2023) 101661

Contents lists available at ScienceDirect

Aquaculture Reports

journal homepage: www.elsevier.com/locate/aqrep

Generation of quantifiable knowledge about delouse treatments of salmon – The case of Hydrolicer®/Hydroflow treatments

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ARTICLE INFO

Keywords:
Aquaculture salmon lice control
Mechanical delousing treatment
Fish welfare, optimization
Lepeophtheirus salmonis
Operational Welfare Indicators

ABSTRACT

Controlling the salmon lice problem is at the very core of the salmon farming industry's growth challenges. One group of methods to control lice is the mechanical treatment methods. By means of these methods, lice can be successfully removed from the fish, but they also impose adverse effects such as stress, hypoxia, loss of scales, skin bleeding, and injuries or mortality. Farming companies are, therefore, interested in finding the optimal timing and the best settings of these methods in order to achieve the best trade-off with respect to louse removal and negative impacts on fish welfare. To achieve this, fish farming companies need to collect data about the interrelations between environmental factors, properties of individual fish or fish groups, the level of lice, fish welfare, and the mechanical treatment. Today, there is a lack of research on how to use the mechanical treatments to provide the best prognosis of delousing results and adverse effects on fish welfare. Therefore, in this paper, we identify available fish welfare indicators from the literature and study how the industry determines, communicates, and applies these indicators. For this purpose, we have conducted interviews with major actors in the salmon farming industry in Norway. Based on this analysis, we suggest that the treatment process should be described by two main processes: fish crowding and treatment onboard, and seven process stages where data should be collected. Our analysis identifies a need for more data from the fish crowding and from the treatment onboard, as well as more data about the biological status of fish in cages before the treatment. There is also a need for a better exchange of data between the cooperating parties (farmer, treatment operator, and support vessels) in a format that addresses both the fish population on average and also the distribution among individuals. We used the Hydrolicer® method for this study because it was easily accessible to us and little has been previously documented about this method, but the results are useful for all mechanical treatment methods.

1. Introduction

For several decades, salmon lice (*Lepeophtheirus salmonis*) has become a severe problem for the salmonid aquaculture and wild salmonids in the Atlantic (Dean et al., 2021; Jevne and Reitan, 2019; Stene et al., 2022; Torrissen et al., 2013; Vollset et al., 2017). A severe infestation of this parasite on salmonids leads to sores, stress, inflammatory response, reduced immunity, osmotic problems, and immunosuppression (Bowers et al., 2000; Finstad et al., 2000). According to Stien et al. (2013), 0.12 lice per cm^{-2} is the limit for salmon survival, and any level above this is lethal.

To fight salmon lice infections, a range of different methods have been developed, such as lice-skirts around cages (Stien et al., 2018), cleaner fish (Overton et al., 2020), pharmaceutical treatments (Aaen et al., 2016), thermal delousing (Grøntvedt et al., 2015; Overton et al., 2019). One group of delousing methods is mechanical treatments. In this group, we find different methods which have in common that the fish are crowded and then pumped into a treatment system where the lice are mechanically removed from fish by means of flushing or brushing (Overton et al., 2019). The system by SkaMik AS (Overton et al., 2019) flushes the fish after removing it from the water and brushes it under transportation. The system by Flatsetsund Engineering AS (FLS) (Gismervik et al., 2017; Nilsen et al., 2010; Overton et al., 2019) and the Hydrolicer® technology by Smir AS (Overton et al., 2019) flush fish in water while it is transported through pipes. The latter two systems are very similar, and the only difference lies in the placement of the dewatering system for lice removal.

Our analyses are on the Hydrolicer® technology. We focus on this

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https://doi.org/10.1016/j.aqrep.2023.101661
Received 24 November 2022; Received in revised form 21 June 2023; Accepted 7 July 2023
Available online 16 July 2023

method because there is a lack of scientific documentation and research for this method (Overton et al., 2019), and it is the method for which we have the best access to data. The treatment process of this technology can be described as follows (Overton et al., 2019): Typically 2–4 days before the treatment, the farmers stop feeding the fish. This reduces the salmons' need for oxygen during the treatment, increasing the ability of the salmon to withstand stress, and reduces the pollution in the water from feces during crowding and treatment (Nygaard et al., 2020). Before and during the treatment, the fish group is gradually crowded in the cage, such that it can be reached by the suction end of the pipes through which the fish are pumped on board to a vessel/barge. After the fish have been pumped out of the cage, the fish pass through a system of pipes with 4–6 stations, where inverse water turbulence "vacuums" make the lice lose their hold on the host. The fish then pass through a dewatering system where the processing water with the detached lice are removed. The lice are then filtered out of the processing water. Finally, the fish are released into the cage.

Although the intention of mechanical delousing methods is to keep lice numbers below threshold levels, these methods lead to adverse psychological and physiological fish welfare effects such as stress, hypoxia, loss of scales, skin bleeding, and injuries or even increased mortality (Østevik et al., 2022; Erikson et al., 2018; Gismervik et al., 2017). Furthermore, the fish become more susceptible to secondary infections and new attacks from sea lice (Noble et al., 2018).

When treating the fish with the Hydrolicer®, the farming company and the treatment operator must make decisions with respect to the crowding time and density, the height of the vessel's treatment system and water outlet above sea level by adjusting the water ballast, the pressures in the HydroFlow transportation pumps, the speed of the fish through the pipes, as well as the pressures in the Hydrolicer® units. These decisions are critical to delousing success on one hand and the loss of fish welfare on the other. It has been pointed out in the literature that the Hydrolicer® has promising potential for optimizing the trade-off between these two goals (Gismervik et al., 2017; Holan et al., 2017). To enable such an optimization, we need to know the interrelations between the number of lice, the condition of the fish as individuals and as a group, the properties of the environment in which the treatment is applied, and finally the settings of the Hydrolicer® to be applied during treatment.

There is only limited empirical data available about Hydrolicer® treatments (Noble et al., 2018; Nygaard et al., 2020; Overton et al., 2019); we have so far only found one study of stress indicators regarding the use of this method (Erikson et al., 2018). There is a continued need to document the effects of this treatment in practical use to gain data and knowledge as a basis for optimizing this treatment and for comparing it with other handling systems and delousing methods (Gismervik et al., 2017). It is necessary to define and collect controllable input data, non-controllable exogenous data as well as output data (data with respect to fish welfare and the delouse effect).

The objective of this paper is, therefore, to identify and describe the state-of-the-art of data collection from delousing treatments in the Norwegian salmon farming industry. Particularly, we aim to understand which data is collected, how it is collected, how representative the data is for describing the phenomenon of fish welfare, what challenges occur in the data-collection process, and how data is used and communicated to maintain or improve fish welfare.

For this purpose, we have conducted a series of semi-structured in-depth interviews with representatives of the farming industry to get an overview of data available in the industry today and how these data are used. These interviews not only reveal which data are collected (or not collected) in different stages of the treatment and farming but also how data is communicated between the farmer and the treatment operator.

2. Materials and method

2.1. Interviews and respondents

To understand the collection, communication, and use of data associated with the Hydrolicer® treatment, we have conducted semi-structured interviews with three representatives of fish farming companies where the Hydrolicer® delousing method was used. The respondents are specified in Table 1. These fish farming companies were chosen, because they were available for our interviews, they are amongst the largest fish farming companies in Norway that use the Hydrolicer® method, and they represent a large part of the industry in Norway. Of the 1071 commercial food-producing salmon- and trout-farming licenses in 2021, the interview partners were responsible for 258, which is 24 % of the industry in Norway. One of the farming companies (Salmar Farming AS) carries out delousing by means of the Hydrolicer®. The other companies depend on external service providers that offer this treatment.

In addition, we have conducted an interview with a pure service provider that offers this treatment to fish farming companies. The service provider was included because it was a supplier of this treatment to two of the three interview partners.

The interviews were performed by telephone. Initially, personal meetings were planned but became impossible due to the Corona pandemic in 2020. The interviews covered questions on what data that were collected, in which step of the treatment process the data were collected, and to what degree were the data shared and used for improvement. The respondent's internal role in the company was to be either responsible for treatment or responsible for fish health.

For the interviews, we prepared a table that contained the suggested indicators in rows and the four process steps of the treatments in four columns. When new indicators came up, we expanded the rows of the table. Through the interviews, we noted in the table the answer to each indicator that came up and noted other comments in the text below the table. The details and comments are described in the Appendix.

After all of the interviews, we summed up the answers in a frequency table, counting "Yes" answers to each indicator and process step. This is shown in detail in Section 4 and in the Appendix.

2.2. Specification of fish welfare indicators and relevant data in the interviews

2.2.1. Categories of indicators

The concept and meaning of fish welfare has been extensively discussed in the literature (Ashley, 2007; Conte, 2004; Rottmann et al., 1992). Stien et al. (2013) and Noble et al. (2018) work with the following definition: "*Welfare is* […] *defined as 'the quality of life as perceived by the animals themselves', and the ability to experience welfare is* […] *part of the emotional monitoring system that guides animals* […] *in getting what they need and avoiding harm and dangers*". Based on this

Table 1
Overview of interviewed fish farmers and service provider that use the Hydrolicer® treatment.

Company	Company's Role	Respondent's Role	Interview time
Nova Sea AS	Fish farmer	Production Biologist	70 min
Mowi ASA, region North	Fish farmer and service provider of Hydrolicer® treatment.	Veterinarian	50 min
Salmar Farming AS	Fish farmer	Non-medicinal treatment methods production manager	85 min
Fish Care Solutions AS	Service provider of Hydrolicer®	CEO	90 min

definition particular physical (respiration, nutrition, thermal regulation, etc.) and behavioral needs (safety, social contact, rest, etc.) of Atlantic salmon are identified (Stien et al., 2013). The satisfaction or frustration of these needs can then be linked to measurable attributes of the production system (temperature, lighting, and water quality) through performance criteria from different animal welfare disciplines, like "pain" and "illness" from a veterinarian perspective or "aggression" and "abnormal behavior" from a ethological perspective (Bracke et al., 2002; De Mol et al., 2006; Stien et al., 2013).

While many authors have described individual qualitative and quantitative indicators of welfare, there are also attempts to establish systematic assessment protocols or aggregated measures of overall welfare. Three examples are described below:

- The welfare standards for farmed Atlantic salmon of the Royal Society for the Prevention of Cruelty to Animals (RSPCA) developed in 2002 (RSPCA, 2021),
- The welfare assessment protocol developed by the Norwegian Veterinary Institute (Grøntvedt et al., 2015),
- The Salmon Welfare Index model (SWIM) by (Stien et al., 2013) which is based on the overall welfare assessment model of (Bracke et al., 2002).

In our analysis, we depart from the collection of indicators by Noble et al. (2018) that contains operational welfare indicators for different land- and sea-based production systems as well routines and operations like delousing, vaccination, transport, etc. These indicators are furthermore categorized as environmental, group-based, and individual-based indicators. Laboratory indicators (such as the hepatosomatic index, the cardio somatic index, muscle pH, plasma cortisol, and others, see Noble et al., 2018) that require laboratory equipment and personnel are often collected in special disease situations rather than ordinary treatment situations. Such indicators are, therefore, outside the scope of our interviews.

We focus in this article on operational welfare indicators (OWI) and data that contains information on the impact of the delousing treatment, properties of the crowding process, and environmental data that may affect the process, as well as the actual effect on lice numbers from the process. In this way, we want to find candidates for data that describe both the effect of delousing, the adverse effect on welfare indicators, and the trade-off between adverse effects and the welfare gain from delousing (Holan et al., 2017). Table 2 summarizes the categories of indicators that we will cover throughout the interviews.

For later analytical purposes, we found it useful to describe the environmental indicators as not-controllable variables of the environment that surrounds the fish being treated. To optimize treatments or to adjust an ongoing treatment, we needed to collect data regarding the settings (controllable variables) of the system that is used. The controllable variables such as crowding time, crowding density, and pressure settings can be adjusted during the treatment and affect both the delousing effect and adverse effects on fish welfare (Gismervik et al., 2017).

In addition, delousing success as well as adverse effects on fish welfare will vary depending on biological properties of the fish such as fish size, fasting time (now as an uncontrollable parameter when the actual treatment commences), and indicators associated with fish health and welfare just before the treatment (Gismervik et al., 2017).

Table 2
Proposed operational welfare indicators and treatment data for mechanical delousing.

Individual-based indicators	Group-based indicators	Environment-based indicators
• Skin conditions (scale loss, wounds) • Fin damage • Mouth or jaw damage • Gill histology/ bleeding • Deformities • Eye status and injuries • Opercular damage	• Appetite • Growth • Mortality and cause of mortality • Behavior • Emaciated fish • Health or disease status • Red water • Head/tail entering (treatment) • Scales in water	• Oxygen • Temperature • Salinity • Water velocity • Light • Stocking density • Turbidity • Holding time (treatment) • Time out of water (during treatment)
Treatment results	**Biological properties**	**Controllable settings**
• Number of adult female lice on the fish • Number of preadult (movable) lice on the fish • Number of chalimus (fixed) lice on the fish	• Diseases • Average fish size • Size variance in the cage • Fasting time, hours • Recovery time of appetite since the last treatment	• Crowding density and time • Crowding method, like sweep net, float line, etc. • Crowding oxygen level (0–100 % saturation in seawater) • Density in treatment system (% biomass to water) • Bar pressures on Hydrolicer® units • Water outlet height above sea level, cm (200–350) • Fish velocity through pipe • Water velocity through pipe • Treatment speed, tons /hour • Delivery to new cage or same cage

2.2.2. Process steps where data were collected

To show the effects as the difference between status-before and status-after treatment, it is important to collect data at different steps of the treatment process. For the interviews, we have defined the following process steps (the italic terms in parentheses are used in the tables in Section 3):

1. Data are collected in the cage before the treatment (*Before*),
2. Data are collected during the treatment process (*During*),
3. Data are collected a short time after treatment of the whole cage ended (*After*),
4. Data collected 1–2 weeks after a treatment to see the longer-term effects on indicators like mortality (*Later*).

However, the discussion in Section 4 shows that this division of the treatment process is not sufficient and that we also need data from the cage before crowding, during crowding as well as immediately after treatment exposure.

2.2.3. Sharing of data between fish farmers and the treatment operator

We also wanted to investigate how the collected data was shared between the fish farmers and those responsible for the treatment. In our opinion, relevant data should be shared between the farming company and the treatment operator to analyze in what way the treatment performance changed the situation for the fish in the cage before and after treatment. We wanted to find out to what extent the indicators were available and shared between farmers and the delousing treatment operator (or division) and actively used for improvement. We, therefore, categorized the level of sharing data as follows (the italic terms in parentheses are used in the tables in Section 3):

1. Data shared and used to improve the actual or later treatments (*Shared/used*),
2. Data shared between farmers and the treatment operator but not used (*Shared*),
3. Data collected and registered but not shared between farmers and the treatment operator (*Collected*),

4. Quantifiable data available and described in, for instance, Laksvel, Fishwell, or RSPCA but not collected (*Described*),
5. A scale for the variable is not described in the literature (*No scale*).

3. Results

3.1. Results concerning the categories of the indicators

In each of the following subsections, we discuss one of the six categories of indicators described in Table 2. A detailed overview and comments from each respondent are presented in the Appendix.

Each subsection contains a table that shows the indicators to which the respondents answered "yes". The mid-section shows four columns with the process steps introduced in the previous section. These columns indicate how many respondents collected data in each process step. Blank cells indicate that the collection of data was not mentioned or indicated by the respondents. In the columns with the heading "Sharing", we have registered to what extent each indicator was registered, communicated between the fish farmers and the treatment vessel, and used to adjust the treatment. An "X" indicates that one or several respondents answered positively.

3.1.1. Individual-based OWIs

Table 3 discloses the results from the interviews with respect to the individual-based OWIs. The individual-based OWIs were registered on the treatment vessel/barge. As can be seen in Table 3, the indicators are measured by means of four discrete levels: Level 0 indicates no injuries, and level 3 represents serious injuries. The different levels were described by images that show examples of each level. The staff of the treatment operator classified individual fish with respect to these levels by looking at the fish and comparing it with the images. The collected indicators were used to adjust the settings during treatment. These indicators were also shared both during and immediately after the treatment on the vessel. We did not find any sharing of data between the farmers and treatment operator, concerning the individual-based OWIs collected before the treatment or after the treatment in the cage. The interview partners did not report taking samples of these indicators from the fish in the cage. The crowding process occurs between process step 1 and 2 that was mentioned in Section 2.2.2 and is described as a cause of reduced individual OWIs (Noble et al., 2018).

3.1.2. Group-based OWIs

Regarding the group-based OWIs, the interview partners suggested two new variables, which we initially did not have in our interview guide/table. Particularly, these were scale loss and appetite. As Table 4 indicates, there is no consistent measurement of scale loss and the number of removed lice for the total fish group of one cage. Both scale loss and removed lice were collected in a container on the treatment vessel/barge and handled as waste. The amount was sometimes logged but was not reported to all farmers. Some farmers did register this indicator, and some did not. Concerning "red water" coloration due to gill bleeding, the interviews did not show any collection of this data. Red water is described in the literature on delousing, but no standard for scoring has been developed (Noble et al., 2018). Acute mortality was recorded by either the treatment operator or the farmer's representative and was reported at the end of treatment. Generally, mortality rates are routinely registered in time windows of 7 days by the farmers (described as weekly mortality or 7-day mortality) but not shared with the treatment operator. Swimming behavior during crowding was reported by the treatment operator in the treatment report for each cage if the fish deviated from usual observations. However, a particular scale of swimming behavior during crowding was not applied. Swimming behavior can be observed to indicate how well fish respond to crowding (Noble et al., 2018).

3.1.3. Environment-based OWIs

The environmental OWIs like seawater temperature and algae level was considered important because they affect both the need for oxygen (Noble et al., 2018) and the available oxygen for the fish during crowding. The interview partners regarded temperature as important for the growth rate of the fish and their resilience to scale loss. The environmental data was also used to consider acceptable weather conditions regarding the security of personnel and equipment, and the risk of fish escaping. Escaped salmon from farms threatens wild salmon by transferring diseases and parasites or by interbreeding (Jensen et al., 2010) and is strongly regulated by the Norwegian regulations on technical requirements for aquaculture installations (NYTEK23). Postponing the treatment due to unfavorable weather conditions affects individual OWIs before the treatment or fasting time. The volume and density of fish in the cage before the treatment were used to estimate the treatment plan. The interview partners did not describe any ex-post analysis of the relationships between the environment-based indicators and the delousing effects and welfare indicators.

Responses during the interviews are summarized in Table 5.

The treatment-effect indicators were the most often shared indicators during all process steps, categories, and indicator groups. Samples of lice infection were recorded aboard the vessel/barge, both immediately before the fish passed through the Hydrolicer® sections, and after the treatment by the Hydrolicer®. The samples were used to compute average numbers of sea lice after the treatment and the average percent reduction for the treatment. The samples on board before and after the treatment were not collected at the same time, usually a team first collected an after-treatment sample and then a before-treatment sample, so there would be 20–30 min delay between them. The results were reported to farmers and used by both parties to evaluate the results of the treatment.

3.1.4. Biological properties

The indicators concerning the biological properties of the fish were used to decide when to commence a treatment and what settings to choose for the treatment. Table 7 gives an overview of the responses from the interviews. The interview partners did not describe any communication or analysis of the relationships between the biological indicators together with the treatment settings and the achieved results (target indicators). The interview partners did not calculate or report the variance in the fish size. Normally, the choice of settings is based on the

Table 3
Results of the interviews with respect to individual-based OWIs.

Individual-based operational welfare indicator	Process Step				Sharing				
	1. Before	2. During	3. After	4. Later	1. Shared/used	2. Shared	3. Collected	4. Described	5. No scale
Red belly (graded 0–3)		4			X				
Scale loss (graded 0–3)		4			X				
Wounds (graded 0–3)		3			X				
Snout damage (graded 0–3)		1			X				
Fin injuries (graded 0–3)		4			X				
Gill bleeding (graded 0–3)		4			X				
Eye damage (graded 0–3)		3			X				

Table 4
Results of the interviews with respect to the group-based OWIs.

Group-based operational welfare indicator	Process Step				Sharing				
	1. Before	2. During	3. After	4. Later	1. Shared/ used	2. Shared	3. Collected	4. Described	5. No scale
Appetite (hours to pre-treatment feeding rate)							X		
Acute mortality (% number of fish)			3		X				X
Weekly mortality (% number of fish)	4			3			X		
Extended mortality post treatment				1			X		
Swimming behavior (unusual or not)			1						X
Red water – coloration from gill bleeding									X
Scale loss filtered out to waste container (estimated liters)					X				X

Table 5
Results of the interviews with respect to environment-based OWIs.

Environment-based operational welfare indicator	Process Step				Sharing				
	1. Before	2. During	3. After	4. Later	1. Shared/used	2. Shared	3. Collected	4. Described	5. No scale
Oxygen level in cage (%)	4				X				
Seawater temperature (3–18 °C)	3				X				
Seawater salinity	2						X		
Sea current, knots or meters per second	3	1			X				
Volume of fish in the cage (kg biomass)	3				X				
Density in the cage (kg fish per m^3 volume)							X		
Algae level (0–10 m sea water visibility)	4				X				
Wind velocity, meters per second	3	1			X				
Sea wave height, meters	3	1			X				
Cage Type	4				X				

Table 6
Results of the interviews with respect to indicators of treatment effects (number of lice per fish).

Indicator for treatment result	Process Step				Sharing				
	1. Before	2. During	3. After	4. Later	1. Shared/used	2. Shared	3. Collected	4. Described	5. No scale
Number of adult female lice on the fish	4	3	2	3	X				
Number of preadult (movable) lice on the fish	4	3	2	3	X				
Number of chalimus (fixed) lice on the fish	3	3	1	2	X				

average size of fish as recommended in the system's manual. Some interview partners said that sorting the fish before treatment was more common several years ago but was less likely to be done now. The fasting time before the treatment was sometimes reported in hours and sometimes in days before the treatment. The farmers had a standard for how much time to plan for, depending on the sea temperature. However, if the treatment of some cages deviated from the plan, the fasting time for subsequent cages could be affected. The respondents did not describe any post treatment analysis of the relations between the fasting time and the effects concerning delousing and fish welfare.

3.1.5. *Operational settings in treatment*

The results concerning the operational settings of the treatment system are presented in Table 8. The settings indicators were chosen by the treatment operator and were sometimes discussed with the responsible person for fish welfare in the farming company, typically when the results deviated from the objective. The treatment report per cage contained the settings indicators. The water outlet height over sea level affects the energy of the fish pumps to lift the fish and water onto the processing vessel/barge (Holan et al., 2017) and, therefore, affects both the delousing effect and the adverse effects of a Hydrolicer®. One interview partner said in the interview: "*We know the lifting height is important both for treatment capacity, delouse effect and scale loss, but have not so far had any standard way of measuring or reporting this*".

3.1.6. *Sharing of data between fish farmers and the treatment operator*

The interviews showed that the farmers select data ahead of the treatment and exchange these data with the treatment operator. This data varied from farmer to farmer but usually contained lice numbers, environmental indicators, and biological properties. This exchange was either driven by questions from the treatment operator or if the farmer believed that this data could be of interest for the outcome of the treatment.

The use of settings throughout the treatment was mainly managed by the treatment operator, but was often discussed with those responsible for fish health or the location manager. The settings were chosen according to a manual that prescribed startup settings and adjusted based on the operator's experience. The interview partners did not describe any statistical or systematic analysis of relationships between the environmental indicators, biological properties, and settings on one hand, and individual OWIs, group OWIs, and the delousing effect on the other.

The group-based OWIs were part of the agenda in the farmer's evaluation meetings in the last phase (2–3 weeks after treatment) and were important, especially for the development of lice infection, fish mortality, and appetite. However, the treatment operator did not attend these meetings according to the interviews and did not usually receive any reports. One of the respondents said that: "*We would have liked to see some more interest from the treatment operator regarding the data from the period after treatment*". When asked about this, one treatment operator answered that "*We try to collect this data 2–3 week after treatment, but it is not easy to get in touch with the right contact person for this.*" This essentially means that except for acute mortality, group based OWIs were rarely communicated between the farmers and treatment operators.

The samples of fish taken in the cages before crowding and treatment (process step 1) were communicated to the treatment operator in pre-treatment meetings regarding lice numbers, but the OWIs were not shared in the same way.

The environment-based indicators were communicated before a treatment and used for planning the operations and choosing the settings to be applied during the treatment. For some indicators like wind, sea current, and oxygen level, there were predefined limits and stop-rules for the treatment operator during treatment.

The settings indicators from treatment were also routinely shared between the treatment operator to the farmers on a cage level. When adjusting settings through a crowding, the treatment operator usually performed a new score batch of indicators after treatment and registered these along with the new settings. This was done manually and took approximately 20–30 min.

The interview partners did not describe any post-treatment analysis of relations between the Hydrolicer® settings and the results.

3.2. Findings with respect to crowding

To collect the fish from a cage for treatment aboard a vessel, the farmers used a crowding process that guides the fish to the intake pipes. Crowding the fish in one cage was usually divided into 1–10 intervals, splitting the cage volume by means of a sweep net or float line, depending on the farmer's standard routine. The crowding time and crowding density for the individual fish depend on the total biomass to be crowded, the treatment velocity, and the practical lifting of a cage net or sweep net during the crowding process. Furthermore, the crowding density experienced by individual fish will vary throughout a treatment dependent on when the fish is caught by the suction tubes.

The interviews showed that crowding is considered to play an important role in fish welfare. One interview partner emphasized that "*We reckon crowding to be the most important cause for reduced fish welfare during treatment*".

For treatment systems on barges, the crowding density is an important part of the direct control of the treatment settings, because the fish pass the Hydrolicer® units in cascades rather than individually. The crew lifting nets have a display on deck, showing tons per hour as an indicator of density and velocity, and they use this information as a guide for lifting the nets. The procedure on well boats is different. Here the well becomes an intermediate storage, and by adjusting the sliding bulkheads, the crowding density under the treatment in the Hydrolicer® is controlled.

Data about crowding time, crowding biomass, and treatment velocity were collected and reported. There are guides with illustrations that define the levels 1–5 of crowding density (Noble et al., 2018; RSPCA, 2021), but the interviews did not discover any use of these. Crowding density was reported in the treatment log per cage if a deviation from the standard occurred, but "*The guides from Fishwell* [(Noble et al., 2018)] *and* (RSPCA, 2021)] *are not easy to quantify*" as one of the respondents said. The Fishwell welfare-indicator guide grades crowding density in acceptable, undesirable, and unacceptable groups (Noble et al., 2018), but it is ambiguous what these levels exactly mean.

The total crowding time from the beginning to the end of the treatment was recorded. However, the average crowding time or the standard deviation of the crowding time for the fish was not computed or registered in the treatment reports. There were scanners on the treatment lines that counted the number of individual fish and calculated the volume and velocity. Therefore, it would be possible to collect data that can be used to calculate the crowding time per fish more precisely. We did not find any systematic analysis of crowding data with respect to delousing or fish welfare effects.

One possible indicator of crowding density is the density one can observe when fish are entering the treatment pipes from the crowding. This may be computed from the volume of fish biomass going through the treatment lines, compared to the total volume of water going through the lines. Such density in treatment was not used or communicated, although the system supplier has a guide on what density to use (7–8 % fish biomass in water). Our interviews lead to this indicator being part of the treatment reports at one of the respondent's companies after the interviews.

3.3. Findings with respect to the dispersion of data

All interview partners described the welfare indicators or lice numbers on fish as being represented by averages over the observations in the samples taken. However, variance or dispersion of data around averages were not calculated. Outside the interview guide, one of the interview partners contributed a short table of individual counting of lice on a vessel before treatment and after crowding, taken from one treatment of one location in 2021. The result is presented in Table 9. This table shows the number of adult female lice per fish counted before the treatment. The absolute frequency is the number of fish with the corresponding number of lice in the first column of this table. The data in this table was collected during one treatment consisting of 8 treated cages and is, therefore, not necessarily representative of this kind of treatment, but it illustrates the dispersion of data that we can expect in this biological system, and an average number of 1.34 lice per fish does not necessarily provide sufficient information.

4. Discussion

4.1. Differences in data collection

The results presented in Tables 3–8 show that the data collection varies among the operators of the Hydrolicer®. In some cases, all respondents measure some given indicator at some given process step. With respect to the treatment results (Table 6), we saw that measurements were taken in all of the process steps. Other indicators were measured by a few operators or in a few process steps. We can conclude that there does not exist a common practice for measuring all indicators that describe fish welfare and the delousing effect. Equipment that automatically monitors the status of salmon before, during, and after a delousing operation can reduce the risks associated with treatments of farmed fish (Føre et al., 2018), but such equipment is not found today.

More comprehensive and homogenous data collection across farming companies, across locations, across treatments, and across time would allow the application of statistical methods, the improvements in performance of delousing treatments over time, and a foundation for future automation of some of the treatment settings.

4.2. Sharing data

Our results in Tables 3–8 indicate that not all information is shared and that different practices exist. If fish-farming companies would collect and share more data with the treatment operator before and after the treatment in the cages, then these data could, together with operational data, be better utilized to better quantify the effect of treatments and optimize the settings of the treatment-system with regard to fish welfare and delousing effectiveness.

4.3. Welfare from an individual's point of view

It has been claimed that welfare of each individual rather than that of the group as a whole must be assessed (Broom, 1986; Nilsson et al., 2022). When looking at the delousing treatment by the Hydrolicer®, this claim can be justified. The individuals differ with respect to size, health status, and degree of sea lice infection (number of lice and the phase in the life cycle of lice). Different individuals will experience different crowding time depending on when they are caught by the intake pipes; consequentially, they will experience varying crowding density, oxygen levels, and other environmental indicators, as well as delousing effects and welfare indicators from the crowding alone. When going through

Table 7
Results of the interviews with respect to biological and disease OWIs.

Indicator of biological properties of fish	Process step				Sharing				
	1. Before	2. During	3. After	4. Later	1. Shared/used	2. Shared	3. Collected	4. Described	5. No scale
PD disease, yes/no	3				X				
ILA disease, yes/no	3				X				
CMS disease, yes/no	4				X				
HSMB disease, yes/no	3				X				
AGD gill disease, yes/no	4				X				
Average fish size, (0.2–7 kg)	4				X				
Size variance in cage								X	X
Fasting time, hours	2				X				

Table 8
Results of the interviews with respect to the settings of the Hydrolicer® treatment system.

Indicator describing operational settings	Process Step				Sharing				
	1. Before	2. During	3. After	4. Later	1. Shared/used	2. Shared	3. Collected	4. Described	5. No scale
Crowding method		4			X				
Crowding density								X	
Crowding oxygen level		3			X				
Crowding time in minutes		3			X				
Density in treatment system								X	
Bar pressure on Hydrolicer®		3			X				
Bar pressure on Hydroflow injector		3			X				
Water outlet height above sea level, cm								X	X
Fish velocity through the tube, m /sec		3				X			
Water velocity through the tube, m /sec					X				
Treatment velocity, tons /hour		3			X				
Delivery to a new cage or the same cage		4			X				

the treatment system, the individuals will experience different levels of exposure from treatment units, depending on their position in the pipe, the density of fish near to the individual, the velocity they travel through the pipe, and so on. Our results show that, except for the process of taking samples, the fish are handled as a group and not as individuals during the treatment.

The Hydrolicer® method treats typically 40,000–50,000 individuals per hour according to the respondent from Fish Care Solutions, while one manual measuring procedure typically takes 20–30 min to collect a sample of 20 individuals according to the respondents in our interviews. Although the settings of the Hydrolicer® can be adjusted relatively quickly, there is not sufficient and timely data available because of the time-consuming manual measurements with small sample sizes.

Therefore, the treatment settings aim for an average of biological properties or lice numbers. This means, if adequate settings are used for the average of these properties, an individual fish that deviates from the average will have a less-than-adequate treatment depending on the size of the deviation or combination of deviations in different indicators. It remains an issue for further research what dispersions occur and what the consequences for welfare indicators and delousing effects are.

4.4. Reliability of measurements

Even though standards for scoring OWIs have been established, these are affected by human perception and interpretation, low significance levels, and lack of dispersion calculations. As mentioned above, measurements of the individual-based indicators are taken manually during the treatment. This measurement is both time consuming, and the sample sizes are small. Small sample sizes can lead to insignificant estimates.

Furthermore, the assignment of an unambiguous score is unreliable and prone to subjectiveness, because the status of the individual fish may not perfectly match the images that are used for comparison. Furthermore, such evaluations can differ if they are taken by different persons.

The scale of measure is ordinal from 0 to 3, that is an ordinal level of measurement. When sampling OWIs of fish from cages, one will get a distribution of fish with different welfare scores. Since the scoring levels are not necessarily linear with respect to the measured phenomenon, the results from scores must, therefore, never be presented as average values, or changes in average values, as this gives a misleading representation of the results (Nilsson et al., 2022; Revie et al., 2007).

The ongoing scanning and AI technology development is expected to remedy some of these challenges in the years to come. Replacing manual data collection with video devices and machine learning software may overcome today's problems with sample sizes and measurement errors. This will increase the volume of data collected and the need for assembling the data in a database.

Also, with respect to lice numbers, the reported averages can give unreliable estimates of the true average for the entire fish group. As seen in the Table 9, lice are not evenly distributed as seen in (Heuch et al., 2011), who found a negative binomial distribution of lice numbers. The numbers in Table 9 are moreover unreliable as they are taken in different crowding intervals and from different cages. (Heuch et al., 2011) have found that fish in different cages of the same farming location can have significant differences in lice abundance.

Table 9
Frequency of adult female lice appearances per fish after crowding.

Number of adult female lice	Absolute frequency	Relative frequency in %
0	599	40.67
1	386	26.21
2	228	15.48
3	106	7.20
4	60	4.07
5	41	2.78
6	23	1.56
7	13	0.88
8	11	0.75
9	6	0.41
Sum	**1473**	**100.00**

4.5. System complexity and interrelatedness

From the interviews, we learned that the complexity of a delousing treatment is relatively high, where biological data of the fish and environmental data are combined with technical data from the treatment system. While technical data are easily measured, it is difficult to collect data from samples of a larger number of fish that is treated with one process.

Furthermore, indicators are interrelated. For example, the health status of the fish after the treatment can depend on the biological properties (particularly size) and the health status of the fish before the treatment. The interview partners also mentioned that different observations, like oxygen levels, fish counters, or fish speed are registered but remain unconnected data.

Hence, multi-dimensional datasets that contain all these measurements per individual are either not made or impossible because single individuals are not identifiable before and after treatment. Without such data, it is challenging to analyze what treatment and treatment settings give the best combination of fish welfare and delousing effect for given environmental conditions and the biological status of the fish. Statistical methods like multivariate regression, structural equation modeling, or decision-tree models are ready to be used to study the interrelation between different indicators. However, the data collection is insufficient for such methods, which again build a foundation of further optimizing the fish welfare.

Furthermore, we envision the potential in assembling multi-variate data streams to an online dashboard for the treatment operator. Combining ex-post analyses from earlier treatments with online statistical analyses and optimization, the treatment operator obtains support on how to optimize operational settings in real time.

4.6. Mucus level on the skin

One welfare indicator that was not measured was the mucus level on the skin. Data from this may contribute added information to the other indicators of skin damage of the fish. From the literature, we found that the treatment may reduce the mucus level which is part of the salmon's protection against sea lice (Noble et al., 2018). There may, therefore, be a correlation between indicators that affect the mucus layer, and the time and velocity by which the reinfection with lice develops after the treatment.

4.7. Importance of crowding

As mentioned before, crowding is an essential part of the treatment, and the way it is carried out plays an important role for both lice numbers and adverse effects on fish welfare. First, the crowding process can damage the skin and mucus layer and lead to physical stress (Delfosse et al., 2021; Gismervik et al., 2017; Overton et al., 2019). According to the interviews, crowding affects OWIs like red belly or scale loss. Second, crowding suspected to lead to delousing. Although we did not find literature documenting the delouse effect of the crowding process itself, the increasing use of solutions like the catchLICE® sweep net in delouse treatments indicates that a substantial part of the sea lice disappears from the fish during the crowding process because of the movements of the fish. If data were collected from the cage before crowding, it would be possible to not only compute this effect but also adverse effects from the crowding process before the actual treatment starts.

The operators control parameters of the crowding process like crowding density, crowding time, and oxygen level. Except for oxygen measurements in the crowding, no online data is collected from crowding. After emptying one crowd, the crowding time is registered. If one could measure the volume of water, for instance, with indicators from the length/area of the net in water, the overall crowding density could be computed. New acoustical technology may also measure crowding density overall or in parts of the crowding. Movements of fish in crowding may also be an indicator of stress that is not measured today. Such data could be used to study more accurately the effect on fish welfare, e.g., the impact on fish welfare during the crowding.

4.8. Expansion of process steps

Because of the importance of the crowding, we argue that it is beneficial to divide the overall treatments into one crowding process and one treatment process. We need to collect data before, during, and after each of the two processes and have two data collection steps for the cages after treatment. In this way, we can analyze welfare effects from both the crowding process and the treatment process aboard and analyze the interrelations between these two main processes. Hence, the four process steps that we initially applied are not sufficient. It is rather necessary to look at 7 process steps as illustrated in Fig. 1.

5. Conclusions and further prospects

Finding the best trade-off between lice-removal and fish welfare when treating with a Hydrolicer® is a complex decision, which requires the collection and analysis of a representative amount of data on fish properties and lice numbers from before, during, and after crowding and treatment, as well as data from the treatment settings.

Only if data is available can one successfully establish relationships between the different input parameters (environmental, biological, and settings indicators) and target variables (number of lice and fish welfare indicators). The purpose of this paper was to investigate the process of data collection in the salmon farming industry. From the existing literature on fish welfare, we have collected a range of different indicators that can be useful for the analysis and decision-making, concerning delousing treatments. By means of interviews with respondents from the salmon farming industry, we have shed light on what kind of data is available or can be made available to gain insights for improvements to delousing treatments.

We have found that individual OWIs are well established in literature and applied in the industry. When it comes to environmental and biological indicators, their relation to individual OWIs and their role for the positive and adverse effects of delousing has not been studied in a systematic way.

A particular challenge is the unstable nature of biological data. The variety and dispersion of data is a strong property of biology, where variety is an important part of the survival strategies of species. This leads to ambiguity and uncertainty as to what connections we can draw between input data and target data. When only focusing on the average of observations and not considering the dispersion of observations, one loses many of the tools to study the cause and nature of lice presence and fish welfare.

The discussion in this paper suggests considering a delousing treatment as two main processes both giving effects and adverse effects and that one should consider 7 steps of data collection from these processes. The suggested categorization of indicators from the interviews may then be combined with this 7-step process for analysis purposes. We think this will give a better base for analysis of causality, covariances, and improvement opportunities and may be a good case for multivariate statistical analysis and optimization models.

We focused on the use of the Hydrolicer® technology in the Norwegian salmon farming industry. With some adjustments of the settings indicators used in this paper, we believe the results are applicable to other mechanical treatment methods and other parts of the global fish farming industry. This could be an interesting topic for further studies.

Author statement

We want to thank the reviewers for their comprehensive and valuable feedback. This has contributed to make our paper much more solid,

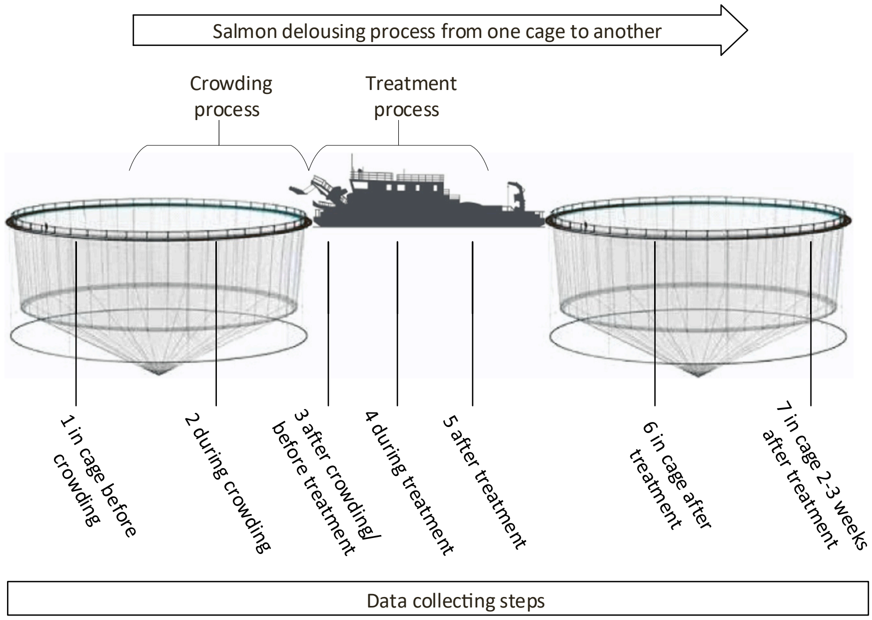

Fig. 1. Process stages in delousing fish with the Hydrolicer®, where data should be collected. In our initial interview we applied four points in the treatment process, where data should be collected. Particularly, the importance of the crowding process implies to expand data-collection to the 7 points in the total treatment process.

both from a theoretically and empirically standpoint but also from the perspective of readability.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Endeavour Management AS is beside the research of this article an owner of a service provider that perform treatments with the kind of technology that is subject for research. Since the research only covers available data and not actual performance or comparisons of performance, we do not consider this to be important conflict of interests.

Data Availability

The data that has been used is confidential.

Appendix

Indicator used	Process Step Number of positive answers.				Sharing				
	1. Before	2. During	3. After	4. Later	1. Shared/used	2. Shared	3. Collected	4. Described	5. No scale
Dependent variables – individual based OWIs									
Red belly (graded 0-3)		4			X				
Scale loss (graded 0-3)		4			X				
Wounds (graded 0-3)		3			X				
Snout damage (graded 0-3)		1			X				
Fin injuries (graded 0-3)		4			X				
Gill bleeding (graded 0-3)		4			X				
Eye damage (graded 0-3)		3			X				
Dependent variables – group based OWIs									
Appetite (hours to pre-treatment feeding rate)							X		
Acute mortality, (% number of fish)			3		X				
Weekly mortality (% number of fish)	4			3			X		
Swimming behavior (unusual or not)			1						X
Red water – coloration from gill bleeding									X
Scale loss in filtered out to waste container (estimated litres)							X		X
Not-controllable variables – environmentally based OWIs									
Oxygen level in cage (%)	4				X				
Seawater temperature	3				X				
Seawater salinity	2						X		
Sea current, knots or meters per second	3	1			X				
Volume of fish in cage (kg biomass)	3				X				
Density in cage (kgs fish per m^3 volume)							X		
Algea level (0-10 m sea water visibility)	4				X				
Wind velocity, meters per second	3	1			X				
Sea wave height, meters	3	1			X				
Cage Type	4				X				
Dependent variables – treatment effects									
Number of adult female lice on the fish	4	3	2	3	X				
Number of preadult (movable) lice on the fish	4	3	2	3	X				
Number of chalimus (fixed) lice on the fish	3	3	1	2	X				
Not-controllable variables –Biological Properties									
PD disease, yes/no	3				X				
ILA disease, yes/no	3				X				
CMS disease, yes/no	4				X				
HSMB disease, yes/no	3				X				
AGD gill disease, yes/no	4				X				
Average fish size, (0,2-7 kgs)	4				X				
Size variance in cage								X	X
Fasting time, hours	2				X				
Controllable variables - from operation settings									
Crowding method		4			X				
Crowding density								X	
Crowding oxygen level		3			X				
Crowding time in minutes		3			X				
Density in treatment system								X	
Bar pressure on Hydrolicer®		3			X				
Bar pressure on Hydroflow injector		3			X				
Water outlet height above sea level, cm								X	X
Fish velocity through tube, m / sec		3				X			
Water velocity through tube, m / sec					X				
Treatment velocity, tons / hour		3			X				
Delivery to new cage or same cage		4			X				

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Comments from interview partner 1:

When considering data ahead of treatment, one also consider which delicing method to use, based on health condition and number of lice.

The farmer is not considering or adjusting the settings of the delicer through treatment, but approve/stop treatment based on ongoing evaluation. The service provider is managing the settings.

Settings data is collected by service provider and reported on cage level

We have a lower limit 8ºC temperature for method, but also consider rising or falling temperature

We do not delouse fish if there is an ILA outbreak

We have an overall rule of 3 starvation days (approx 72 hours) throughout all year, but increase this some when fish have CMS outbreak

When using the Hydrolicer method most incidents is related to crowding deviations

We register mortality as percent number dead through 7 days, 2 and 3 weeks after treatment, reporting increase in percent mortality after treatment

Comments from interview partner 2:

We consider a set of overall judgements when considering Hydrolicer treatment, containing gill condition, wounds, mucus layer. Mucus is typically considered when temperatures are low, and is possible to affect by feed composition used over some time.

There is a prepartion meeting with involved parties some days ahead of tretment, where observed data from fish group is considered.

The service provider is having a dialog with farmer representative about settings used throughout treatment, and is making a report from each cage treated with effect data, OWI data and deviations if observed.

1-2 weeks after treatment there is an internal evaluation meeting where results and lessons learned is discussed. Service provider is not attending and is not receiving data from this, the interviewee would have preferred more after-job calles from the supplier.

We have predefined weather limits for treatment

We do not register group OWIs red water or total scale loss, but deviaton from normal is reported from service provider

Acute mortality is considered unreliable, because acute mortality is a non-discrete variable dependent of time.

Appetite is always registered, but time-to-normal apetite is not registered explicit.

Lice level is registered from cage on the weekly routine

Crowding density is commentet in cage report if deviated, no variable defined.

Comments from interview partner 3:

Skin health status is considered before choosing delicing method. There is a pre treatment meeting planning the operation.

Most service providers are part of internal organization, farming data and treatment data is registered in same database. Farmer has their own supervisor/representativ attending through treatment.

Dead or damaged fish is dissected on vessel to register cerebral bleeding or hart damage, and is reported.

The treatmetn is evalueted in a meeting 2 weeks after treatment.

Size variance is not a registered variable, but is discussed in planning meeting.

Fasting time registered as days without feeding

Weather is commented in cage log, there are standard weather limits for treatment

Appetite is always registered, but time-to-normal apetite is not registered explicit.

Litres of lost scale in waste container is reported.

Comments from interview partner 4:

The planning meeting varies among farmers, some have a scheme of data, some have a short presentation. The type of data varies.

The general status of fish health is commented, but not neccesary with data.

Some farmers have a scale for HSMB disease spread, some have only a notation of presence

No data of size variance, but variance is commented in deviations

No data of crowd density, but variance is commented in deviations

Lice counting result from treatment seem to be used as the weekly counting of lice this week for reports to authorities.

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