|**Risk assessment of 21 land-based aquaculture systems in Norway – what can be learned?**

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Abstract:

This study presents a comprehensive risk assessment of 21 land-based aquaculture facilities in Norway from the GJENTEK-project using a standardized risk evaluation methodology developed by Akvaplan-niva, Norway. Facilities varied widely in age, technology (FTS, HYB, RAS), and production scale, with assessments focusing on technical and operational risk factors affecting fish mortality. Results showed no consistent link between system complexity and overall risk; rather, effective design, operational routines, and redundancy were key to risk mitigation. The findings emphasize the importance of robust system design, informed operational practices, and continuous monitoring to ensure fish welfare and reduce economic loss in land-based aquaculture.

1. Introduction

In recent years, the aquaculture industry in Norway has faced challenges related to undesirable events and mortality in land-based systems for Atlantic salmon. These incidents, which predominantly occur in land-based smolt production facilities but are also expected to occur in land-based facilities for larger salmon, pose serious concerns for fish welfare and may result in high mortality and substantial economic losses.

As the Norwegian salmon industry moves towards increased production of larger smolts on land, it simultaneously shifts a greater portion of risk from sea to land. This risk is mainly related to extended production time on land and larger biomasses, involving higher investments in equipment and production capacity. The complexity of these systems, particularly in recirculating aquaculture systems (RAS) and hybrid flow-through systems (HYB), further compounds these risks. These advanced systems require integrated solutions for oxygenation, CO_2 removal, pH adjustment, and nitrification (Hillmarsen, 2018), making them more exposed to technical failures and operational challenges.

Key factors for maintaining control in these complex facilities include biological and technical skills, equipment and systems functionality, biosecurity, and water quality management. While proper operation and monitoring of RAS can potentially stabilize and improve fish welfare conditions (Hjeltnes et al., 2012), these systems are not without their challenges. Previous risk assessments have highlighted issues such as high nitrite levels, gas supersaturation, overfeeding, and problems with insufficient particle removal that remain relevant today (Sommerset et al., 2024).

A recent concern is the increased risk of hydrogen sulfide (H_2S) formation, especially in systems using seawater (Letelier-Gordo et al., 2020; Rojas-Tirado et al., 2021; Bergstedt et al., 2022). This risk is particularly pronounced in RAS, where particle accumulation can create conditions conducive to H_2S production. The difficulty in identifying clear causal relationships in mortality events often leads to H_2S being cited as the culprit by process of elimination, highlighting the need for more comprehensive monitoring and analysis.

To address these challenges, the industry is focusing on risk-reducing measures such as improved system design to avoid dead zones and particle sedimentation (Hillmarsen, 2018), as well as efforts to bridge the gap between planned production capacities and achievable production. The importance of technical assessments and risk evaluation in land-based aquaculture systems cannot be overstated, not only for ensuring operational efficiency and fish welfare but also for securing assets and enabling farmers to adequately insure their investments.

A systematic approach to risk assessment, based on standardized methodologies and objective analysis of various risk factors, is crucial. The compilation and sharing of data from risk assessments across different land-based facilities offer significant potential as source for reference data and benchmarking, facilitating learning, enabling early warning systems, and improving the handling and mitigation of key risk factors.

The insurance industry has an important interest in this area, recognizing the high value of both the facilities and the biomass they contain. The Norwegian insurance company Gjensidige has contributed significantly to this field by sharing an extensive dataset from risk assessments of 21 land-based aquaculture systems from the GJENTEK-project, all evaluated using a common standardized methodology developed by Akvaplan-niva.

The primary objectives of these risk assessments and subsequent analyses are to reduce mortality, improve fish welfare, and mitigate economic risks. By increasing fish farmers' awareness of potential risks and enabling them to implement corrective measures, this approach aims to create a more resilient and sustainable land-based aquaculture industry. This introduction sets the stage for a detailed exploration of the risks, challenges, and potential solutions in land-based aquaculture systems, underlining the importance of continued research and collaboration in this rapidly evolving sector.

2. Method

This study is based on 21 risk assessments of different land-based aquaculture facilities in Norway, including 18 smolt and post-smolt facilities for Atlantic salmon (*Salmo salar*), one salmon hatchery, one smolt facility for rainbow trout (*Oncorhynchus mykiss*) and one juvenile facility for lumpfish (*Cyclopterus lumpus*).

The facilities varied in age from the early 1980s to the newest one completed in 2022. In terms of production capacity, the annual biomass output ranged from 220 tons to 3,500 tons. The plants represented various technology types including FTS, HYB, and RAS systems, incorporating both Moving Bed Biofilm Reactor (MBBR) and Fixed Bed Biofilm Reactor (FBBR).

The facilities were risk-assessed according to a standardized protocol and risk matrix, AkvaRisk-Land. All evaluations were conducted by the same team of evaluators, providing a basis for comparison of land-based aquaculture facilities in Norway.

The risk assessments were limited to evaluation of fish mortality as the ultimate consequence. Risks that may affect e.g. disease, escape, and fire were not included in the assessments, although these can also impact fish welfare and lead to fish mortality. The method is summarized in Figure 1.

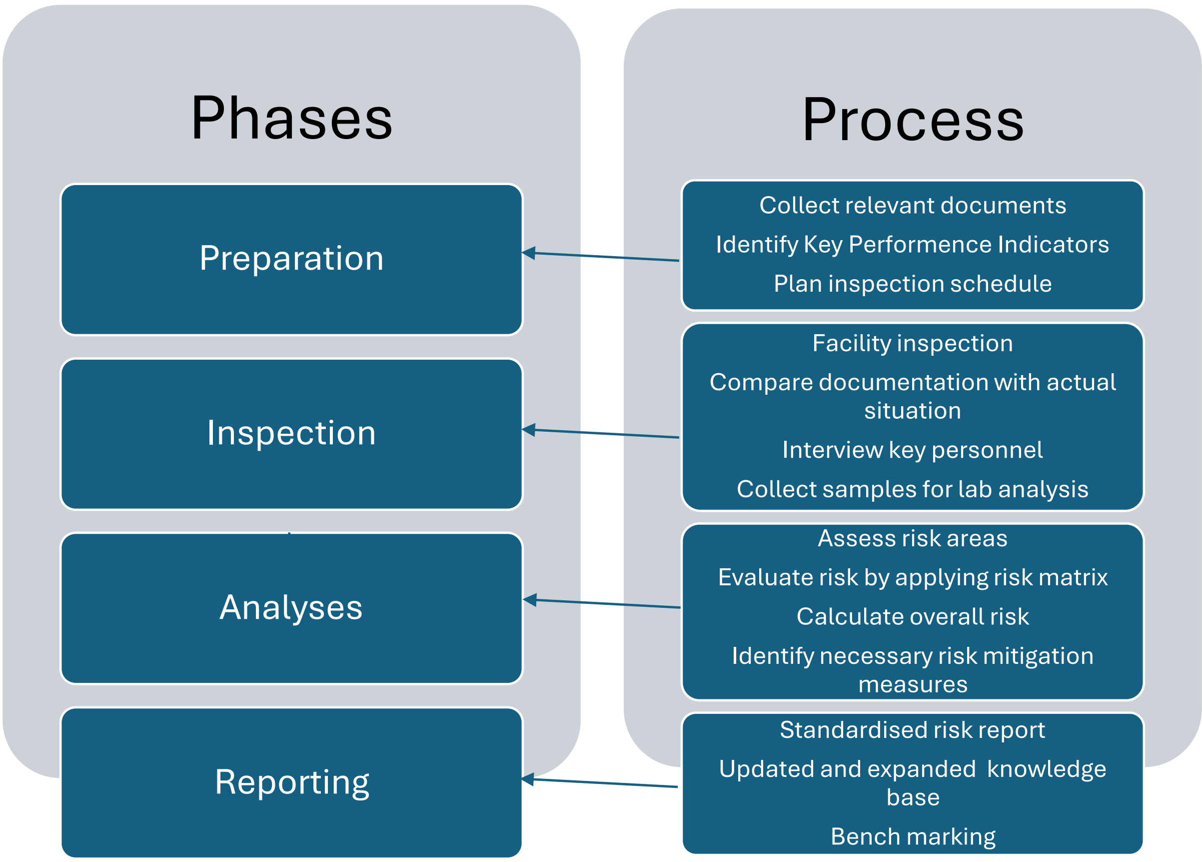

Figure 1. Flow diagram for the risk evaluation method based on principles from the Akvaplan-niva procedure.

The risk assessment process was divided into three phases: preparation, inspection, and analysis.

- The preparation phase involved a comprehensive collection of all relevant documents, including standardized documents and key performance indicators.
- The inspection phase was carried out according to a planned schedule, where various risk areas (themes) were addressed, and documentation submitted in advance was compared to the actual conditions at the facility.
- During the inspection and sampling (for later laboratory analyses) at the facility, a systematic review of the various departments and risk areas in the facility was conducted. Information about critical conditions was gathered through interviews of experienced personnel (operations managers, technical managers, coordinators), focusing on events during the last three years, relevant operating procedures, and internal control systems. In addition, a physical review of the facility was conducted for a comprehensive evaluation of the infrastructure.

Evaluated risk areas

The risk evaluation was based on available documentation and inspection of the various risk areas reviewed during the site visit. The evaluated risk areas (themes) were organized in a thematically standardized form to ensure that technical documentation, common infrastructure, water chemistry measurements, sensor data, operating procedures, and deviation management, as well as the various departments, were methodically assessed (Table 1).

Table 1. Checklist of various areas (themes) and risk factors for risk assessment.

Nr/ID	Risk areas from Documentation	Nr/ID	Risk areas from Inspection
ID	**Facility drawings and quality documents:**	ID	**Freshwater**
Nr 1-1	Organization chart and responsibilities	Nr 9-1	Water source
Nr 1-2	Facility layout drawing	Nr 9-2	Pumps
Nr 1-3	Map of water intake and discharge	Nr 9-3	Pipelines
Nr 1-4	Piping and instrumentation diagram	Nr 9-4	Filter
Nr 1-5	Drainage drawing	Nr 9-5	UV
Nr 1-6	Detailed drawing of component placement	Nr 9-6	Raw water quality
Nr 1-7	Capacity calculations		**Seawater**
Nr 1-8	Damage history for the last three years	Nr 10-1	Pumps
Nr 1-9	Risk assessment	Nr 10-2	Pipelines
Nr 1-10	Contingency plans (technical fail or water quality challenges)	Nr 10-3	Filter
Nr 1-11	Alarm log	Nr 10-4	UV
Nr 1-12	Procedure for testing alarms	Nr 10-5	Raw water quality
Nr 1-13	Requested key figures		**Temperature regulation**
Nr 1-14	Facility water quality data from the last year	Nr 11-1	Energy plant or heat pumps
Nr 1-15	Sensor data through a cycle from hatchery to delivery	Nr 11-2	Water exchange
	Surveillance, alarm system and response		**Power and emergency supply**
Nr 2-1	Response time	NR 12-1	Main power supply and distribution
Nr 2-2	Alarm in all units	NR 12-3	Emergency power generator
Nr 2-3	Alarm for water chemistry (facility in general)		**Hatchery department**
Nr 2-4	Oxygen alarm	Nr 13-1	Hatchery cabinet water stoppage
Nr 2-5	Power failure alarm	Nr 13-2	Hatchery cabinet flooding
	Water source and water supply	Nr 13-3	Hatchery cabinet temperature
Nr 3-1	According to maps and drawings	Nr 13-4	Degassing
Nr 3-2	Catchment area	Nr 13-5	Filter
	Seawater	Nr 13-6	UV
Nr 4-1	Pumps	Nr 13-7	pH - measurements
Nr 4-2	Filter	Nr 13-8	O2 - measurements
Nr 4-3	Pipeline	Nr 13-9	TGP - measurements
	Emergency supply energy and oxygen	Nr 13-10	CO2 - measurements
Nr 5-1	Generators	Nr 13-11	Water quality and gill metall during inspection
Nr 5-2	Maintenance routines/plans	Nr 13-12	The facility`s own water quality and gill metall data
Nr 5-3	Alarm points		**First feeding department (same for other departments)**
Nr 5-4	Oxygen tank	Nr 14-1	Tank
Nr 5-5	Oxygen generator	Nr 14-2	Water supply and dianage
	Freshwater	Nr 14-3	Filtration
Nr 6-1	Pipeline	Nr 14-4	Temperature regulation
Nr 6-2	Degassing	Nr 14-5	Degassing
Nr 6-3	Pumps	Nr 14-6	UV and internal disinfection
Nr 6-4	Oxygen cones	Nr 14-7	Alarm
	Temperature regulation	Nr 14-8	Emergency power
Nr 7-1	Heat pumps	Nr 14-9	Oxygen addition
Nr 7-2	Additional heating source	Nr 14-10	pH - measurements
	Fish tanks	Nr 14-11	O2 - measurements
Nr 8-1	Hatchery	Nr 14-12	TGP - measurements
Nr 8-2	First feeding	Nr 14-13	CO2 - measurements
Nr 8-3	Juvenile	Nr 14-14	Water quality and gill metall during inspection
Nr 8-4	Smolt	Nr 14-15	The facility`s own water quality and gill metall data
Nr 8-5	Post-smolt		**Shared infrastructure**
		Nr 15-1	Oxygen tanks and distribution
		Nr 15-2	System for pH regulation
		Nr 15-3	Fish transportation system
		Nr 15-4	Dead fish system
		Nr 15-5	System for sludge treatment

Preparation

The submitted documentation was reviewed and assessed for adequacy and compliance with regulatory requirements for internal control systems in Norwegian aquaculture. Noncompliance with these requirements was considered deviations and were normally evaluated with increased risk. In addition, the internal control system and reporting may reveal deficiencies in capacities, such as, emergency systems (electric power, oxygenation etc.), water requirements in relation to permits, historical events and closure of deviations, routines for service and maintenance.

Prior to the inspection, historical WQ sensor data and results from raw water (freshwater and seawater), process water, and tank water analyses, were requested. This enabled the evaluators to make a detailed plan of the inspection, where to sample water and which documents to call for during the inspection. In addition to WQ sensor data and analyses, contextual factors such as feed burden and water exchange rates were considered to interpret the results more accurately.

Facility inspections

The physical inspection included a review of all departments, including evaluation of emergency power systems, power infrastructure, water management, oxygen supply systems and how this match with the documentation. The inspections and assessments were adapted to facility-specific conditions, such as the number of departments and the use of different technologies.

To assess risks related to water quality (WQ), three main sources of data were included: (1) results from water and gill analyses sampled during the site visits, (2) facility-specific sensor data collected from the previous year, and (3) submitted laboratory reports documenting water quality at each facility.

Site visits were timed to coincide with periods of peak production to simulate conditions of operational stress, although this was not always feasible. Therefore, long-term water quality data provided by the facility played a crucial role in understanding the total water-related risks, particularly under high-production conditions. In cases where WQ data was not shared or available, the lack of information was interpreted as a potential risk.

The Risk Matrix

Risk assessment of the various risk areas and associated risk factors was conducted using a standardized risk matrix (Table 2), with calculated level of risk (R) based on the combination of likelihood (L) and consequence (C): Risk (R) = L × C.

The risk scores were categorized according to:

- Low risk (green): 1–8,
- Medium risk (yellow): 9–18
- High risk (red): 20–36

These categories were further assigned numerical values of 1 (low), 2 (medium), and 3 (high) for aggregation purposes.

Each risk area (e.g., Alarm Systems, Documentation, etc.) received an overall score based on the average of the individual risk factor scores within that area. Similarly, the overall facility risk was calculated as the average score across all risk areas.

Table 2. Risk matrix for assessment of technical documentation, infrastructure, and production departments in land-based facilities (AkvaRisk-Land).

Risk matrix

Consequence						
6	6	12	18	24	30	36
5	5	10	15	20	25	30
4	4	8	12	16	20	24
3	3	6	9	12	15	18
2	2	4	6	8	10	12
1	1	2	3	4	5	6
	1	2	3	4	5	6
	Likelihood					

Likelihood (documentation)

6	No information
5	Verbal from third party
4	Verbal from the facility
3	Verbal and email or equivalent
2	Written documentation from the facility prepared according to request
1	Original documentation delivered before inspection

Likelihood

6	Occurs regularly (daily or weekly)
5	Occurs 1-3 times per month
4	Occurs annually
3	Occurs within a 5-year period
2	Occurs less than every 5 years, but is a known issue
1	Few has experienced the event, or it has never happened

Consequence

6	More than 80% of the fish die
5	30 to 80 % of the fish die
4	2 to 30 % of the fish die
3	Permanent damage to the fish and increased mortality over time
2	Reduced growth and temporary increased mortality (between 0.2 and 2% per year)
1	Only temporary stress on the fish if the deviation is closed within 24 hours

For risk scores between two categories, a thorough evaluation was made to determine the resulting category. The thresholds applied for these averages were: **Low:** ≤1.1, **Medium:** >1.1 – 2.0 and **High:** ≥ 2.1.

This method ensured a standardized yet adaptable approach to risk evaluation, enabling tailored assessments while maintaining consistency. Resulting in a comprehensive risk overview through systematic documentation and data analysis. By combining technical evaluations with practical operational insights, the assessment served as a robust tool for identifying and mitigating potential risks in complex facility environments.

In assessing the likelihood of undesirable events and understanding the scope and severity of potential consequences, historical records of deviations and incidents, industry experience, scientific literature, and recommended thresholds (e.g., for water quality parameters) was considered.

The evaluation of water quality results was based on established threshold values for individual parameters from scientific literature and NIVA's database for raw water used for aquaculture purposes (the WQ database). Slightly different threshold values were used to evaluate RAS, FTS and HYB. For the evaluation of H_2S-related risks, two independent methods, (Passive samplers, Teasdale et.al., 1999; Spectrophotometrically, Letelier-Gordo et. al., 2020), to measure dissolved sulfide (S^{2-}) were used. Depending on pH, temperature and salinity sulfide (S^{2-}) can dissociate into H_2S gas in water. Both methods have low detection limits, slightly above background levels in RAS (<1 μg/L; Lien et.al., 2022). To reduce the likelihood of false positives, H_2S was only registered as a risk factor if both methods indicated presence of H_2S above the detection limit.

Results and Discussion

The assessment of 21 land-based aquaculture facilities covered a wide range of facilities differing in size, complexity, technological configuration, water treatment systems, and age. The variation in facility age also reflected the development of technology over time. All FTS were among the oldest facilities assessed and this illustrates a shift toward more water-efficient solutions as RAS, with expansion on sites with limited water available. Many of these FTS facilities has added new departments based on RAS, and HYB systems were often chosen in areas with relatively better water availability, where a simpler system was preferred.

Facilities that started up as FTS and gradually expanded with RAS components often developed stepwise. In some cases, departments were sourced from different suppliers, resulting in varied system designs at the facility, occasionally combining both MBBR and FBBR within the same facility. A similar pattern was observed in early RAS-based operations that developed over time by adding multiple RAS units.

Newer RAS facilities, typically supplied by a single provider and built in one large development phase, featured streamlined layouts and well-documented systems and identical departments, with adjustments made solely to scale for increasing biomass.

As water consumption is reduced and treatment demands intensify, both the number of risk factors and the severity of potential consequences associated with system deviations, such as events that could lead to fish mortality, tend to increase. This escalation is due to the greater operational complexity and higher production intensity in advanced systems.

Despite the general correlation between system complexity and elevated risk, the assessments identified both low-risk and high-risk cases across all facility types (see Fig. 2). The risk scores among the facilities ranged from well below the "Low Risk" threshold (1.1) to upper-level of the "Medium Risk" interval (>1.1 – 2.0). Although no facilities fell into the "High Risk" category (≥2.1), it is noteworthy that both the two highest and the two lowest overall risk scores were found in facilities utilizing RAS or FTS+RAS configurations.

This highlights that while more can go wrong in complex systems, effective risk mitigation is achievable. Even in highly advanced configurations, risks can be successfully managed through robust facility design, appropriate technological solutions, and well-implemented operational practices, including continuous monitoring, preventive maintenance, and stringent control routines.

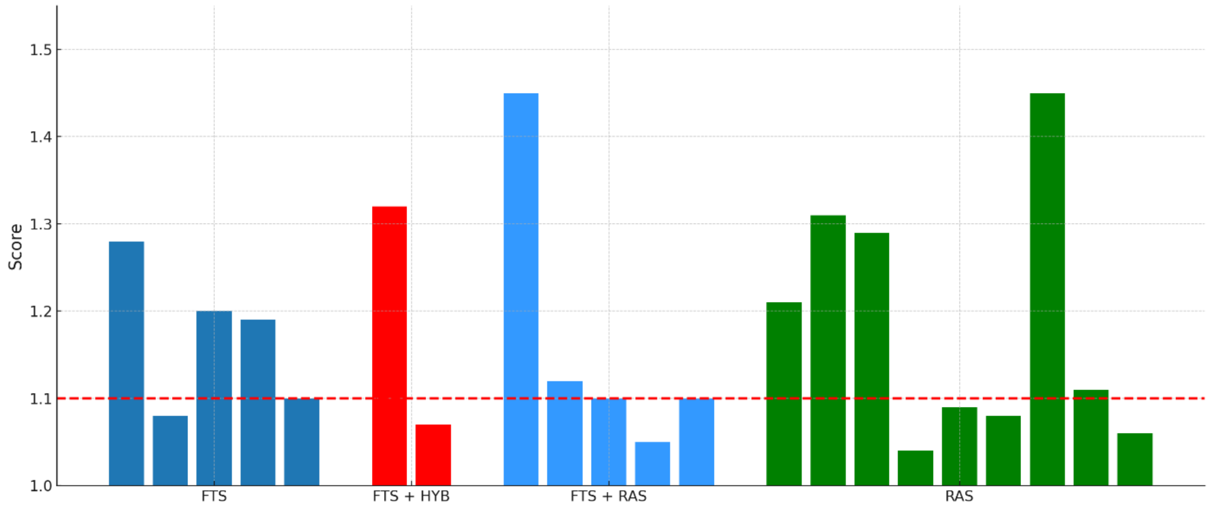

Figure 2. Overall risk score for the 21 land-based aquaculture facilities. The four different facility types are defined as FTS (Flow Through System); FTS + HYB (facilities combining departments with FTS and Hybrid Systems); FTS + RAS (facilities combining departments with FTS and RAS); RAS (Recirculating Aquaculture System). Dotted line represents the threshold between low and medium risk. None of the facilities were found to have high overall risk (≥ 2.1).

1. Evaluation of Technically Related Risks

A total of 11 technical risk areas were identified based on the assessment of 21 land-based facilities (Figure 3). These represent risk areas from the checklist (Table 1) and risks evaluated as medium or high according to the methodology (Table 2). Detailed descriptions of each risk area are provided below.

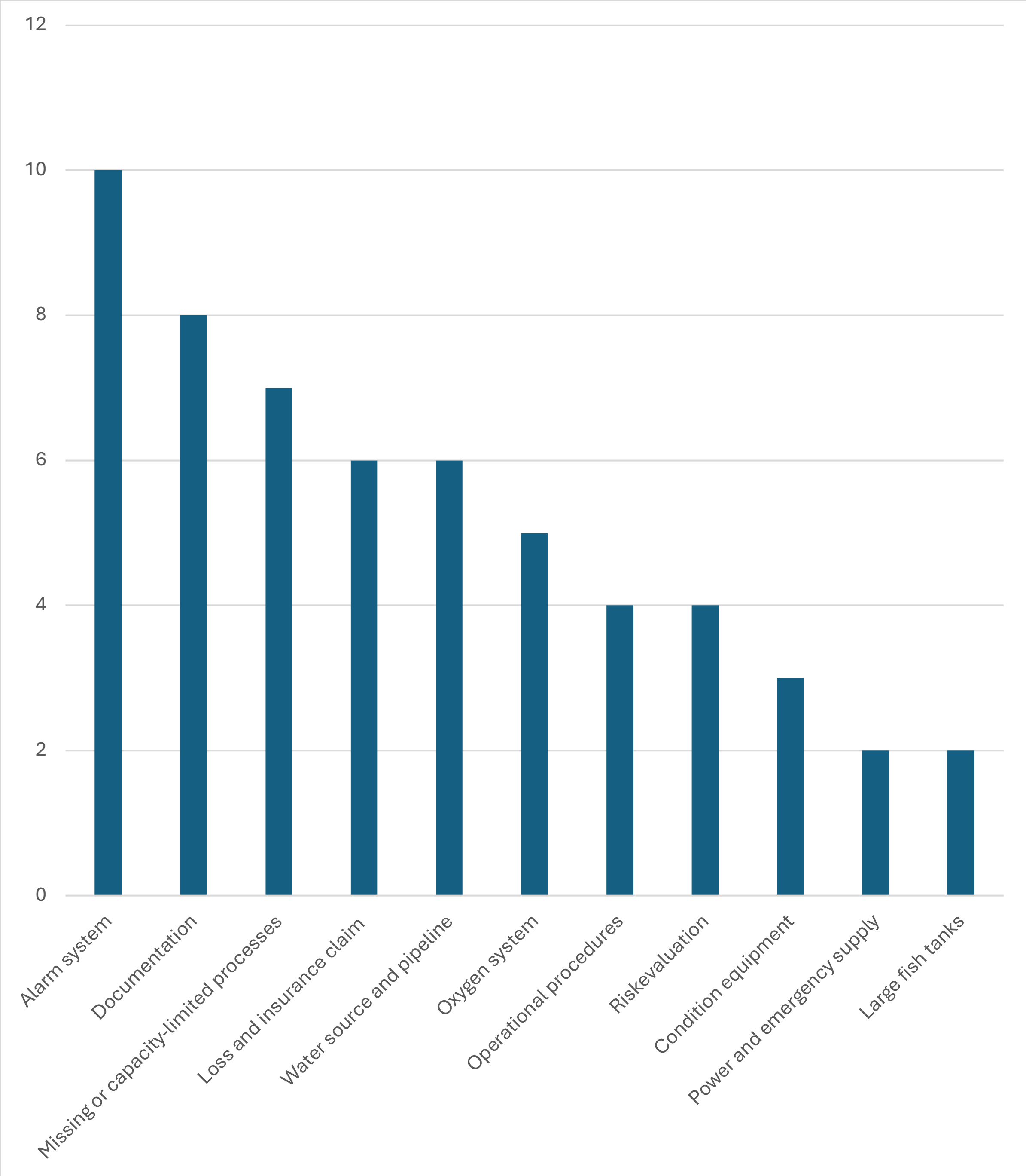

Figure 3. Overview of the 11 risk areas categorized with medium risk or more (x-axis). Y-axis showing the number of facilities (cases). A total of 21 facilities were evaluated.

1.1 Alarm System

There were some cases of missing alarm points related to critical processes such as oxygen control and pH adjustments (based on lye). There were also cases with insufficient monitoring of water flow which increases the risk of not detecting critical stop in water supply. These issues were primarily associated with hatchery and first feeding departments.

Deviations related to sensors and alarms were related to insufficient numbers of sensors deployed for early detection of deviating water quality and regulation. There were cases where a department with a high number of tanks were relying on only one oxygen sensor placed in one of the tanks. This gave alerts on stop in water or oxygen supply to the department, but not on the condition for the individual tanks. It also reduced the possibility to regulate individual tanks. Regulating oxygen based on a single sensor may give imbalanced oxygenation in the different tanks due to different conditions among the tanks, particularly stocking density. Even several sensors may be required in large fish tanks where gradients in water quality may occur.

There were several instances where the alarm system was configured with only a single call-out mechanism, leaving no backup in case of system failure. In another case, alarm severity levels and priorities, such as whether alerts were sent via text message or triggered loud audible signals, had not been defined. Additionally, there were cases where physical alarm indicators (e.g., lights and sound) were missing on-site, reducing the likelihood that alarms would receive the necessary attention.

The potential consequences of inadequate monitoring, insufficient control mechanisms, lack of user-level separation for alarm administration, and missed alarms include the risk that critical situations may go unnoticed and unaddressed. Regular inspection and calibration of sensors, setpoints, and alarm thresholds must therefore be emphasized as essential measures to mitigate these risks.

1.2 Technical Documentation

In several cases there was a lack of required technical documentation of equipment and processes, particularly in older facilities. These deviations were mainly related to missing or outdated records, with critical details such as the layout and condition of the piping network often unavailable. At one facility, there was no documentation of the actual water flow path, posing significant challenges for maintenance, system upgrades, and risk assessments.

In some instances, entire departments were omitted from the technical documentation, highlighting the risk of relying on outdated records, especially in older facilities that have since been upgraded or expanded. Additionally, there were cases where the condition survey (systematic inspection and assessment based on regulatory requirements, e.g. Norwegian technical standard NS 9416:2013) was not carried out in accordance with the requirements.

At two facilities there were examples of limited documentation of capacity and inadequate calculations in key processes, where substantial redesign and retrofitting were necessary to enhance water treatment due to inadequate calculations in the design phase. These modifications included improving the efficiency of particle removal, biofiltration, and degassing systems (see capacity-limited processes). At one facility, the amount of biomedia in the Moving Bed Biofilm Reactor (MBBR) had to be reduced to optimize circulation patterns, lowering the filling degree from 45–50% to 35–38%. At another facility, an underestimation of the design criteria for make-up water hindered the achievement of the targeted production capacity.

One facility failed to provide thermal photography of its electrical infrastructure, which was required as part of regular inspections mandated by insurance companies for fire prevention. These inspections play a vital role in preventive maintenance, ensuring technical reliability, and early detecting potential failures.

1.3 Missing or Capacity-Limited Processes

Issues related to missing processes were observed at two facilities, specifically due to the absence of a degassing system following temperature regulation. This increases the risk of gas supersaturation. Both facilities utilized flow-through systems (FTS) and had been in operation for several years.

Limited capacity for temperature regulation was noted at several facilities, particularly in FTS + HYB systems, where water temperature fluctuated with changes in intake water. Some facilities addressed this by using multiple water intakes at varying depths to regulate temperature through mixing. The primary risk associated with inadequate temperature regulation, especially cooling, is the increased oxygen demand at higher temperatures, coinciding with a reduction in oxygen availability due to lower saturation levels. Limited cooling capacity during the summer posed a notable risk at several facilities, including one recirculating aquaculture system (RAS).

At one facility, all dead fish handling was carried out manually, which is labor-intensive and particularly challenging in large tanks or during periods of elevated mortality. In some cases, there was insufficient capacity to manage high mortality events. Such incidents can reduce water exchange from the tanks or cause blockages in water outlets, increasing the risk of tank overflow.

Several examples were observed where inadequate systems limited the effectiveness of water treatment processes. These issues involved systems for particle removal, degassing, and water flow through tanks and Moving Bed Biofilm Reactors (MBBRs). At one facility, undersized biofilters resulted in insufficient nitrification capacity relative to the system's design specifications based on daily feeding rates.

Two facilities experienced inadequate water flow and poor mixing of biomedia within their MBBRs, leading to stagnant zones prone to clogging. Both systems utilized two bioreactors in series, with water flowing between them over a screen. In areas susceptible to clogging, particles accumulated, increasing the risk of hydrogen sulfide (H_2S) formation.

There were also instances of inadequate degassing systems, which not only failed to sufficiently remove dissolved gases but, in some cases, contributed to elevated total gas pressure (TGP). In one case, a vacuum degasser was unable to achieve the required vacuum conditions, resulting in inefficient gas removal. In another case using a design based on the air-water countercurrent principle likely produced microbubbles under pressure from the main pumps, ultimately increasing TGP in the fish tanks.

Incidents of insufficient particle removal were associated with the design of fish tanks and water treatment components, causing a risk of trapping particles. Mitigation measures included redesigning and retrofitting tank outlet systems and implementing partial-stream particle removal within the treatment loop.

1.4 Loss and Insurance Claims Within the Last Three Years

Six of the 21 evaluated facilities (28%) had insurance claims related to mortality incidents within the past three years. Three of these facilities experienced two or three such incidents. The incidents were associated with non-conformities between actual operations and planned procedures, documentation of event sequences, and expert analyses of fish and water quality. However, the causes of mortality were not always possible to verify with certainty. More specifically the nature og these incidents were:

A case where high mortality in the hatchery and egg cylinders occurred without identifying a clear cause. An unsolved case was assessed as a high-risk case.

In another case increased mortality at the start-up of a new post-smolt department was observed, associated with unfavorable water velocity, poor gill health (ciliates), or altered aluminum chemistry following mixing sea water and freshwater to a department. Technical improvements, including reducing water velocity and increasing residence and mixing time for saltwater before water entering the fish tanks, were later implemented as a risk mitigating measure.

An incident leading to mortality occurred at a facility after vaccination and subsequent inter-departmental movement. This was associated with low calcium levels causing osmoregulatory problems for the fish. As a mitigating measure, calcium levels were regulated to > 1 mg/L.

Three facilities using sea water reported incidents related to H_2S formation in the MBBR. Poor biomedia mixing and areas with stagnant water in the bioreactor where organic matter could accumulate and form H_2S was hypothesized as the causing factors. It is often difficult to give definite conclusions on issues where H_2S may be involved, and such suspicions is often based on ruling out other plausible causes based on lack of other deviating parameters and the nature of the mortality pattern (acute, lack of clear symptoms).

Two mortality incidents were associated with the use of chemicals to regulate water quality. One incidence was caused by a malfunction of a by-pass control valve, which resulted in wash water containing NaClO entering the makeup water for fish tanks after cleaning the membrane filter. In another incident during fasting prior to transport, increased particle load was likely a contributing factor, as foam-suppressing chemicals caused a significant release of biofilm into the system and instant increase in turbidity.

In another, unresolved case, acute mortality, possibly caused by hydrogen sulfide (H_2S), occurred in a fish group undergoing starvation prior to transport. The triggering factor was hypothesized to be related to the use of liquid ozone (LOZ) prior to the starvation period, applied to increase the redox potential (Eh) and reduce the organic particle load in the water during feeding. Once feeding stopped and particle load decreased, the addition of LOZ was also halted, leading to a sudden drop in Eh. If small accumulations of H_2S were already present in the system at sub lethal levels, a shift from a high Eh (200–300 mV) to a low Eh (-100 mV or below) could result in more production of hydrogen sulfide (H_2S). When LOZ is reintroduced after the starvation period to manage organic load, the redox potential rises again, and H_2S levels go down again. Therefore, identifying H_2S as the direct cause of mortality is often difficult due to its transient presence and the complexity of redox chemistry in the system.

In general, these examples illustrate the complexity associated with chemical use. Chemicals are often applied to address symptoms, such as high organic load, without resolving the underlying root cause. It is essential to identify and address the root cause to reduce reliance on chemical interventions and mitigate associated risks.

One facility reported an incident involving increased total gas pressure (TGP), which occurred due to changes in flow conditions when two of four fish tanks in a shared circulation system were emptied. This led to air being drawn into the system upstream of the main pumps, thereby increasing TGP. Additionally, foaming in the degasser, commonly observed during periods of fish starvation, may further reduce degassing efficiency.

1.5 Water Source and Pipeline

Two cases involved poor protection of water sources from pollution or external hazards due to their proximity to trafficked roads and other activities within the catchment areas of nearby rivers. This posed a potential contamination risk that could impact the entire facility.

At two facilities, improper installation of water pipelines was observed. Specifically, pipe rupture valves had not been installed, and pipe clamping was found to be inadequate. These deficiencies increased the risk of uncontrolled water loss, potentially compromising operational continuity and safety.

One facility experienced limited water access due to regulatory restrictions combined with seasonal reductions in water availability. This constraint posed a significant operational risk during certain times of the year.

Another facility reported poor water quality resulting from inadequate water treatment capacity. The lack of a particle removal system, critical for maintaining optimal water conditions, led to high turbidity levels in incoming water sourced from a lake with a dimictic mixing pattern during specific periods of the year.

At one facility, the risk of freezing and subsequent water loss from the main water source was particularly high, especially before a stable ice cover had formed. This issue was especially critical for flow-through systems (FTS) without water reuse capabilities.

Finally, one facility treating intake water through a membrane filter lacked a bypass option for the filtration system. As a result, in the event of a system failure or if water demand exceeded the filter's treatment capacity, there was no way to divert flow or switch to a backup treatment method. This represented a major operational risk that could lead to water shortages.

1.6 Oxygen and Emergency Oxygenation

Issues related to improper installation or layout were observed at one facility where super-oxygenated water was routed through a pipeline positioned high above the fish tank level. This configuration increased the risk of bubble formation, water traps, and, in the worst-case scenario, water loss. At another facility, inappropriate valves (ball valves) were used to regulate pressure in the emergency oxygen system, posing a risk of inadequate pressure control.

At one facility, poor protection against external hazards was observed, where an oxygen pipeline was left unprotected and exposed to risks such as collisions, snow removal activities, and other mechanical impacts. While the tanks and evaporators were well protected, a single pipeline leading into the facility was exposed at ground level, making it vulnerable to physical damage, for example, from vehicles.

One facility lacked a proper emergency oxygen system, as required by fish welfare regulations. The existing system relied on electrical power and pumps to deliver oxygen to the tanks, meaning that in the event of a power outage, the facility would be unable to supply emergency oxygen to the fish.

Another facility faced limited regulation capacity for oxygen levels. Oxygen was supplied via super-oxygenated water introduced into the main water supply and distributed across multiple tanks. Due to limited regulation capabilities for individual tanks, there was a risk of suboptimal oxygen concentrations, potentially compromising fish health.

1.7 Operational Procedures

In some facilities, insufficient or missing operating procedures were observed. Appropriate routines for developing and updating procedures and protocols are essential to ensure staff training and systematic operations.

One facility had inadequate on-call arrangements, as it lacked a 24-hour on-call system. Furthermore, staffing levels and response times were not aligned with the facility's risk profile or operational complexity. This posed a significant risk in emergency situations requiring immediate intervention.

Several facilities experienced deficiencies in maintenance routines. Critical infrastructure was not inspected regularly, and maintenance activity logs were insufficient. In one case, filters located before the hatchery cabinet had not been checked, increasing the risk of water loss due to clogging or contamination.

Issues related to the implementation of new technology without adequate supporting procedures were also raised. In some cases, new and untested technologies or designs were introduced without the necessary operational manuals, routines, or training. One such case involved the implementation of a membrane filtration system for intake-water, while another concerned the commencement of full-scale production without a clear operational understanding of interdepartmental coordination, both of which increased the risk of system and operational failures.

At one facility, changes were made to the production strategy without updating operational procedures. These changes affected critical parameters such as temperature, salinity, feeding, and lighting regimes. As these variables have direct impacts on fish health and system performance, the lack of evaluation and risk assessment introduced new, unmanaged risks. Proper documentation and risk assessments should be completed before implementing such changes to avoid unforeseen complications.

1.8 Risk Evaluation

Systematic risk assessment is a mandatory requirement and essential for identifying and evaluating all potential risk factors. This process provides the foundation for implementing improvements, establishing preventive measures, and integrating procedures aimed at minimizing operational, environmental, and biological risks. Conducting structured and recurring risk assessments is particularly important in aquaculture, where complex interactions between biological systems, infrastructure, and external environmental conditions can significantly impact fish welfare, biosecurity, and production stability.

As part of the risk assessment, a critical scenario analysis is required. In one case, it was found that the risk evaluation process did not adequately consider critical scenarios such as water loss, oxygen system failure, and power outages. Although the facility in question operated as a smaller FTS, such scenarios should still be thoroughly addressed within the internal control framework. In another evaluated case, the risk of algae contamination in the intake-water was not properly assessed, despite a documented history of similar incidents at the facility.

At one facility, the risk evaluation system was outdated due to a lack of established routines for systematic review and revision. This was especially concerning given that the facility had recently undergone expansion, doubling its production capacity. An updated risk evaluation was particularly important to identify risks introduced by the technical upgrade, especially if new technologies or procedures were implemented, and to account for the increased risk associated with the increased biomass (increased mortality consequences by major failures).

Another facility faced elevated risk due to an insufficient evaluation of newly implemented technologies. A new intake water treatment system based on membrane filtration was introduced without conducting the required risk assessment beforehand. This lack of prior evaluation increased the likelihood of unforeseen technical and operational deficiencies or system failures.

1.9 Condition of Equipment

The unknown condition of equipment poses a significant risk related to inappropriate maintenance schedules, technical failures, and unstable operational processes. At one facility, certain components of the water treatment system could not be inspected. This included an MBBR system with no documented inspection or maintenance history, representing a potential risk to its capacity and stability in regulating water quality.

Depending on the robustness and usage of materials, wear and tear can lead to the deterioration of infrastructure. At two facilities, fish tanks were found to be delaminated or in poor structural condition. This degradation increased the risk of tank rupture, as well as the potential formation of hydrogen sulfide (H_2S) due to stagnant water accumulating in areas affected by water intrusion.

1.10 Power and Emergency Supply

In general, land-based aquaculture facilities invest significantly in securing power supply, as power outages halt water circulation and can cause severe fish mortality. An exception is where water is supplied by gravity. All facilities had backup power from diesel generators; however, two facilities lacked redundancy and were heavily dependent on a single generator. If this generator failed, the facility would lose all water circulation, particularly critical in RAS systems, where continuous flow is essential and the response time to prevent significant impact is short.

Not all facilities had sufficient backup power coverage for all critical systems. Some lacked emergency power for temperature regulation, heat pumps, and other essential components. However, across the industry, backup power supply is generally highly prioritized. Most of the evaluated facilities demonstrated strong redundancy measures, including multiple power sources, backup connections to local power stations, and on-call agreements with local electrical service providers, some of which included high-voltage support.

1.11 Large Fish Tanks

To efficiently increase production capacity, space utilization, and operational efficiency, the size of fish tanks is increasingly being expanded. Two facilities operated fish tanks with volumes exceeding 2,000 m^3, which poses elevated risks due to the significantly higher biomass concentration within a single unit. This increases the potential impact of any system failure, as it could affect a large number of fish.

Additionally, large tanks may present challenges related to vertical and horizontal water quality gradients, which can become more pronounced due to the high circulation volume. Previous evaluations (from 2022) identified significant risks associated with large tanks, primarily due to limited operational experience and a lack of proof of concept demonstrating that functional requirements were met. Since then, the industry has gained more experience and insight into the operation of large fish tanks, and several associated risk factors are now better understood. As a result, the perceived likelyhood of some of these risks has, in certain cases, been reduced.

2. Evaluation of risks related to water quality

In general, the evaluation of the 21 land-based facilities shows that risk associated with water quality depends on the intake water source and degree of water treatment, as well as the degree of use, reuse and recycling of the water. The overall risks in water chemistry (WQ) were often multifactorial and mainly related to metal toxicity, organic matter, nitrogen compounds, supersaturation of gases (Total Gas Pressure-TGP) and H_2S (Figure 4). Details on these risks are presented in chapters 2.1 to 2.5.

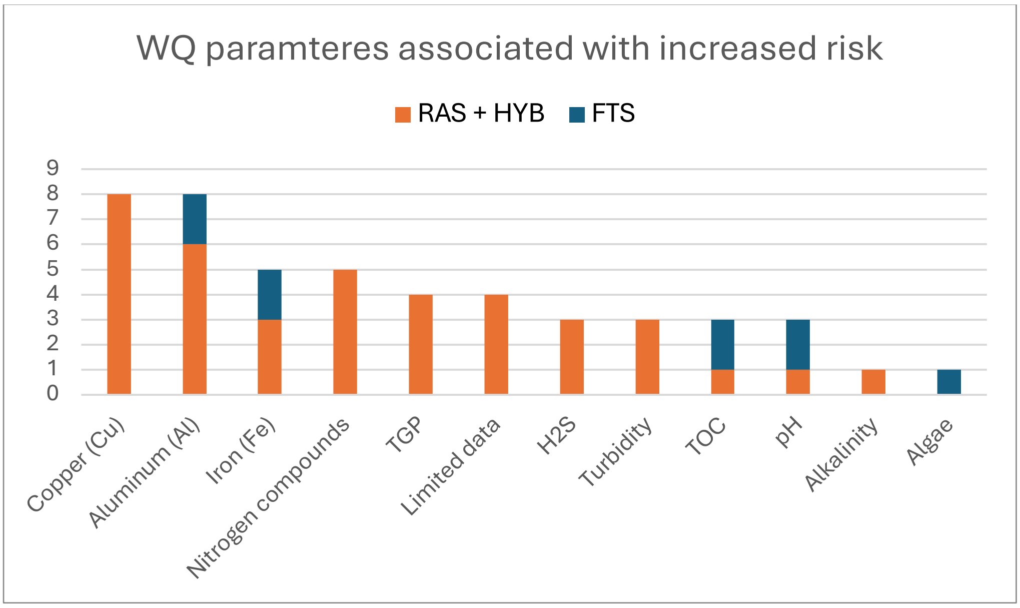

Figure 4. Risk categories related to water quality, in orange RAS (n=14) + HYB (n=2) and in blue strict flow through systems, FTS (n=5). Five of the RAS facilities also had flow-trough systems in pre-smolt departments, but we mostly sampled the smolt departmets which are more vulnerable to risk and also have higher insurance value.

The results also indicate a slightly higher overall risk score in facilities with elevated salinity (Figure 5). This may indicate increased risk with increasing use of seawater, but there were also variations in overall risk score between facilities with similar salinity. Since most of the facilities with elevated salinity were RAS, this may also indicate increased risk with RAS technology. However, the low salinity facilities were approximately half FTS and half RAS technology (~45/55), with little difference in overall risk scores, indicating similar risk between FTS and RAS at low salinity.

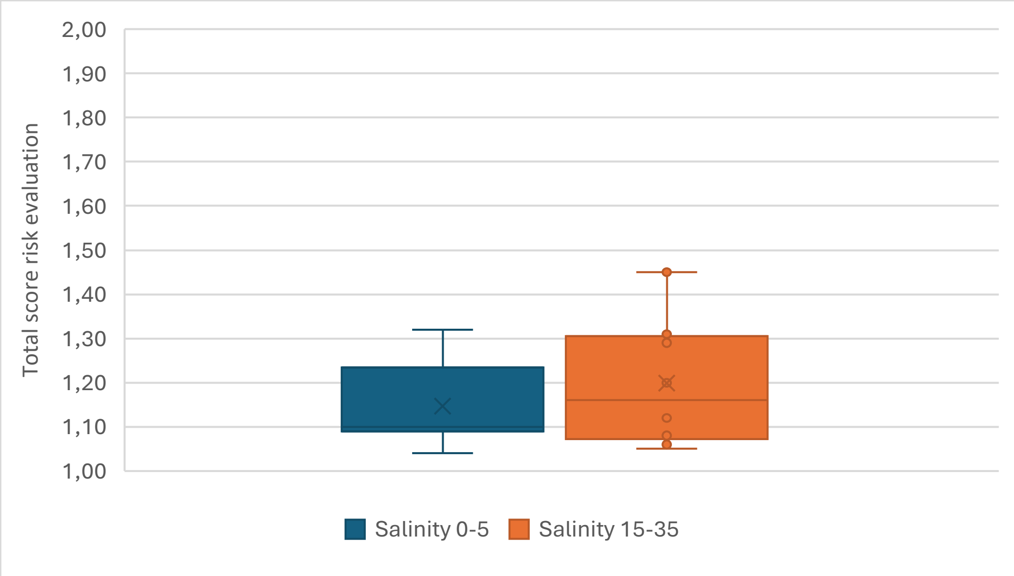

Figure 5 Total risk scores of facilities using maximum 0-5 ppt (blue, n=9) and 15-35 ppt (orange, n=12). The box represents 75% of the data extending from the first quartile to the third quartile. Among the first group of 0 – 5 ppt salinity were 4 FTS, 1 HYB,2 RAS and 2 KOMBI FTS+RAS. Among the group of 15-35 ppt facilities was 1 FTS, 1 HYB, 7 RAS and 3 KOMBI FTS+RAS.

2.1 Metals

In RAS, waterborne copper was the most frequent factor associated with elevated risk (Figure 4). It is not uncommon to have copper along with other feed ingredients accumulating in systems with low water exchange (Martins et.al., 2009). We specifically addressed water-Cu to Cu-accumulation on fish gills relative to safe thresholds (<6 ug Cu/g gill tissue; Berntssen et.al., 1999), to evaluate the risk. In facilities using freshwater, the potential harmful effects on fish were mostly related to humic bound aluminum and iron, combined with variations in pH and organic material that can harness colloidal particle bound metal species. Iron toxicity is more complex to address since it is mostly ferrous iron (Fe^{2+}) that is toxic for fish. Ferrous iron is mostly found in groundwater sources which is not often used as intake water in Norway, but there are also regions in Norway with high amount of humic bound iron in surface water which can accumulate on fish gills (Teien et.al., 2008). However, ferrous iron is normally oxidized to insoluble ferric iron (Fe^{3+}) by aeration and can be seen as brownish deposits, which can be removed before it enters the fish tanks. Accumulation of metals on gills was more prominent in FTS but was also detected on fish in RAS, especially at sites using brackish water. A few RAS facilities operated with salinities in the range of 1 – 15 ppt with increased risk for remobilization of bioactive aluminum in so called “toxic mixing zones”, if not mitigated with sufficient silicate dosing of the freshwater prior to seawater addition (see Rosseland et.al., 1998, Teien et.al.,2004, Åtland et.al., 2004).

2.2 Effects of organic matter

To evaluate the effect of organic load, turbidity, total organic carbon (TOC), nitrogen compounds and microbial heterotrophic activity, were measured in the water samples. The results from each facility are not straightforward to compare, since the concentration of organic matter is greatly affected by feed load and water exchange rates which varied greatly from facility to facility. In general, the results indicate a higher particle load in RAS compared to FTS, as expected. However, a few RAS systems had relatively low turbidity, TOC and heterotrophic activity, which indicate that RAS also can be operated with similar water quality to FTS. Organic particles have previously been shown to affect smoltification and growth of salmon (e.g. Bø, Leif, 2023) as well as increased heterotrophic activity of microorganisms (Pedersen et.al., 2019), which in turn can have negative downstream effects, due to increased oxygen consumption and CO_2 production from microorganisms. High organic load can also have detrimental effects on nitrification in the biofilter (Michaud et.al., 2006), due to competition between heterotrophic microorganisms and nitrifying bacteria over limiting growth factors. When oxygen is limited, certain bacteria groups can utilize nitrate and under certain circumstances also sulfate (SO_4^{2}) as terminal electron acceptors, which can promote H_2S production (Letelier-Gordo et.al., 2020). This is why the combination of high organic load and seawater is considered to have elevated risk. For the RAS systems that were sampled, the average value for heterotrophic activity was slightly below published background values for RAS systems, (Rojas-Tirado et.al., 2018, 2019). For FTS, the value was generally much lower, as expected, due to higher make-up water (MUW) usage.

Feed burden relative to the water exchange rate and particle removal are key operating parameters that influence accumulation of organic matter in aquaculture systems. The need for make-up water will vary between different types of technology FTS, HYB and RAS. For example, some RAS systems are designed for higher specific make-up water consumption (liters/kg feed) compared to others. In practice we observed that some operators choose to use more make-up water during periods of high feeding rates to facilitate dilution, which can also be related to suboptimal water treatment systems. For systems which cannot recycle water (FTS), freshwater availability during parts of the year is critical. We have observed facilities using both FTS and HYB technologies with limited water access, which negatively affected risk factors in WQ at peak production. Some of the RAS and FTS facilities used more make-up water (MUW) than design criteria to mitigate risk. However, this was not possible for all facilities since they had limited amounts of freshwater available. MUW capacity is a critical factor in diluting strategy and on average less water was available for dilution in RAS and HYB compared to FTS. In RAS facilities the overall risk factors in the water depended more on technology performance and implementation and optimization (operational procedures), which again is a function of experience, competence and training.

2.3 Nitrogen parameters

Elevated Total Ammonia Nitrogen (TAN) and nitrite (NO_2-N) concentrations may represent a risk to fish in aquaculture (e.g. Rosten et.al., 2004). TAN will be available in two state forms: unionized ammonia (NH_3) and ionized ammonia (NH_4^+). The relative concentration of these two forms depends mainly on pH, but also on the salinity and the temperature of the water. It is the unionized NH_3-form that is most toxic to fish; this means that the pH will generally determine whether a given TAN concentration is toxic or not. Nitrite (NO_2^-) is an intermediate in nitrification, the oxidation of TAN to nitrate. The relative concentration of these nitrogen compounds may indicate how the biofilter performs. Four RAS were observed to have elevated levels of TAN and/or NO_2^-, and three of them were run with high salinity. It was not investigated whether any of these RAS operated with changing salinities, but in general, stable salinity affects nitrification less (e.g. Navada et.al., 2019). Since unionized ammonia (NH_3) concentration is pH dependent and nitrite (NO_2^-) toxicity decreases with elevated chloride concentration (Gutierrez, 2019), rapid changes in pH should be avoided, but the use of seawater can mitigate the toxic effect of elevated nitrite concentrations.

2.4 Total Gas Pressure

Total Gas Pressure (TGP) and the risk of total gas supersaturation of the production water was evaluated based on the facility's own measurements. Increased risk associated with total gas supersaturation (>100% TGP) was mostly found at facilities with elevated salinities (15 – 35 ppt) (data not shown) and exclusively in RAS. Super oxygenation is not uncommon in land-based aquaculture and can contribute to total gas supersaturation. This indicates that total gas supersaturation occurs more frequently in complex water treatment systems such as RAS, probably due to extensive use of pumps, high oxygen saturation and use of brackish water, since mixing waters with different salinities and temperatures can induce total gas supersaturation (Pulg et.al., 2018). In addition, it can be more challenging to degas seawater RAS compared to freshwater RAS (Moran, 2010), adding more complexity to such situations.

2.5 Hydrogen Sulfide (H_2S)

Among the 21 land-based facilities evaluated, we found three cases of H_2S at levels in the range of 2-10 ug H_2S/L in water sampled on-site, all in RAS. In two of the three cases this coincided with high turbidity and TOC in the water. Two of these RAS facilities used salinities from 15 ppt and higher and the third used a salinity below 5 ppt. which indicates lower probability of H_2S production in low salinity systems. Sulfate (SO_4^{2-}), is the substrate for sulfate reducing bacteria (SRB) and sulfate mainly comes from seawater. An increase in sulfate can incrementally increase the risk of H_2S depending on oxygen levels and organic material (e.g. Letelier-Gordo et.al., 2020). Since H_2S is toxic to fish at very low concentrations (Bagarinao, 1993), even a small increase in sulfate can induce H_2S production by SRB under specific conditions. According to the limited scientific data available, the background values of H_2S in RAS facilities is <1 ug H_2S/L (Lien et.al, 2022) and concentrations between 5 - 10 ug H_2S/L can induce mortality in post-smolt (Lazado et.al., 2024) and influence behavior and appetite (Ciani et.al., 2024). NIVA has previously seen cases of mortality in smolt at levels between 20-50 ug H_2S/L and Bergstedt and Skov., 2023 reports acute threshold levels for post smolt at <60 ug H_2S/L. Based on the results from our survey, the occurrence of H_2S was most likely a factor of seawater usage combined with accumulation of organic particles in the system. These two factors are critical for the formation of biofilm where SRB can produce H_2S under anoxic conditions.

Concluding remarks

The assessments of 21 land-based aquaculture facilities, varying in size, technology, and water treatment intensity, revealed no consistent pattern linking increased complexity, water reuse, or specific system types (FTS, HYB, RAS) to higher overall risk. While more advanced systems like RAS were associated with greater operational complexity and production intensity, both low- and high-risk scores were observed across all facility types. Notably, the two highest and two lowest overall scores were found among facilities using RAS or FTS+RAS, demonstrating that effective risk management is achievable even in highly complex systems.

The somewhat high proportion of medium-risk scores among FTS facilities may reflect the influence of fewer departments, where isolated risks have a stronger impact on the overall average. RAS facilities, while more frequently linked to deviations in water quality, typically involved parameters expected to accumulate with water reuse, such as nitrogen compounds and metals. Low-risk outcomes in some RAS facilities were associated with robust system design, adequate treatment capacity, and strong operational routines.

System resilience also depends on design and operation. FTS facilities often rely on gravity-fed intake water, making them less vulnerable to power outages. RAS, with minimal use of intake water, are less exposed to external water quality issues but are more sensitive to internal failures. Mechanical breakdowns, sensor faults, or power loss can escalate rapidly due to their integrated nature.

Most facilities showed good redundancy and backup systems for critical resources like water, oxygen, and electricity. However, personnel at facilities with a longer operational history typically exhibited greater awareness and had progressively refined their practices over time. In contrast, higher risk was more common during start-up phases, implementation of new technologies, or shifts in production strategies, stages that require time to build system understanding and improve design.

The key risk factors related to water chemistry were more critical for the overall risk score in RAS facilities compared to FTS/HYB, because of the increasing complexity of water treatment and the accumulation of some compounds. The risk of H_2S production was higher in RAS and increased with more use of seawater, but our results also indicate that this risk can be mitigated by proper water treatment, good measurements and good routines, since several seawater RAS did not have problems with H_2S.

There were several mortality cases where H_2S was suspected as the cause. All of these cases were in facilities with MBBR systems and involved design and mixing issues causing particle accumulation. These observations highlights design and operational challenges with MBBR. However, it is often difficult to draw definitive conclusions in cases where H_2S may be involved, as suspicions are typically based on the exclusion of other plausible causes. These assessments are often supported by the absence of other abnormal parameters and the nature of the mortality pattern, which is usually acute and without clear clinical symptoms.

Finally, increased awareness around chemical use is needed. In many cases, chemicals were applied to resolve acute issues like particle buildup or foam, but all potential consequences were not adequately assessed. While chemical treatment may offer short-term relief, addressing root causes, such as improving solid removal or using physical foam control are generally a more sustainable and effective approach.

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