“Latvian and Lithuanian conjunction - Improvement of Baltic salmon and pikeperch rearing methods for more sustainable, resilient and healthy fish populations” (SPPwelfare)

FISH HEALTH INDEX MODEL

Deliverable D.3.2.1

Institute of Food Safety, Animal Health and Environment "BIOR" Riga,

Latvia 2026

Document is produced by the Institute of Food Safety, Animal Health and Environment "BIOR" within INTERREG project SPPwelfare “Latvian and Lithuanian conjunction - Improvement of Baltic salmon and pikeperch rearing methods for more sustainable, resilient and healthy fish populations”

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The project is implemented within the Interreg VI-A Latvia–Lithuania Programme 2021–2027. More information about the programme on the www.latlit.eu and the official website of the European Union www.europa.eu.

The project implementation period is from March 1, 2024 till February 28, 2026.

Total project budget is 497 146.00 EUR. funding of European Regional Development Fund is 397 716.80 EUR. The total eligible project budget of the scientific institute “BIOR” is EUR 293,000.00 EUR, where co-funding of European Regional Development Fund is 234 400.00 EUR and state co-financing is 20% (EUR 58,600.00 EUR).

This project is co-financed by the European Union.

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Introduction

The Fish Health Index Model is designed to provide a quantitative assessment of overall fish well-being by integrating key biological and physiological indicators into a single composite score. The model uses measured variables such as size, weight, smoltification stage, and pathology markers to evaluate health status in a standardized way. By translating raw biological data into a structured scoring system, the index supports objective decision-making in fish quality assessment and helps determine readiness for release into natural environments. This model is intended to improve monitoring efficiency and ensure more reliable evaluation of fish population health.

The modeling process

The semantic modeling process is built to transform biological measurements into standardized health scores using predefined logical formulas rather than raw observational data alone. The model applies a rule-based scoring architecture where each biological variable is assigned a categorical value based on clinically or biologically meaningful thresholds.

The process begins by collecting primary fish health indicators, including morphometric parameters, developmental stage markers, and pathology observations. Each variable is then processed through conditional classification formulas that convert continuous or categorical inputs into normalized index scores.

The model applies hierarchical weighting logic where critical health determinants are prioritized. Threshold-based IF-functions are used to assign discrete semantic values reflecting biological quality classes. These values are then transformed into standardized partial scores.

The final Fish Health Index is generated by summing or averaging the weighted semantic components, producing a composite indicator of physiological readiness and health status. The model maintains interpretability by preserving rule transparency while allowing scalable application across datasets.

This approach provides modeling by emphasizing biological relevance, computational simplicity, and decision-support functionality in fish health evaluation.

For our modeling, we defined relevant health needs in salmon rearing. A variety of individual, herd and environmental indicators were chosen. The chosen indicators were assigned a welfare level, and an indicator score (IS) was calculated. (See table 1.)

$$IS_{i,j} = \frac{\mathrm{NL}_i - \mathrm{RL}_{i,j}}{NL_i - 1}$$

Where: S_{ij} – calculated score
NL_i – total number of levels for indicator *i*
RL_{ij} – rank of the specific level (1, 2 3, 4)

These indicators were integrated into a weighting system, where, based on literature, we determined the importance of each indicator – weighting factors (WF). (See table. 2)

$$WF_i = \left(\sum_{wc} \max(WS_{wcl})\right)_{ILbest\ i} - \left(\sum_{wc} \min(WS_{wcl})\right)_{ILworst\ i}$$

Where: ILbest.i. is the best indicator level
ILworst.i.is the worst indicator level of the i the welfare indicator.
WSwcl is the weighting score assigned to the indicator level, based on scientific research.
After calculating the weighting factors, a relative weighting factor (RWF) was calculated. (See table 3).

$$\mathrm{RWF}_i = \mathrm{WF}_i \times \left(\sum_{j=1}^{m} WF_j\right)^{-1}$$

Where: m - the total number of indicators in the model.
WFi and WFj - the weighting factors of indicator i and j
ISi – indicator score for indicator i
From there we calculated the indicator welfare scores (IWS) and the FHI, respectively. (See Fig. 3)

$$\mathrm{IWS}_i = IS_i \times RWF_i$$

Where: IS - indicator score;
RWF- relative weighting factor

$$FHI = \sum_{j=1}^{m} WF_j$$

Where: m - the total number of indicators in the model.
WFi and WFj - the weighting factors of indicator i and j
ISi – indicator score for indicator i (Stien et al., 2013; Petersen et al., 2014).

Review of welfare indicators used in the project

Temperature

Water temperature is one of the most influential environmental variables governing the physiology, growth, health, and survival of Atlantic salmon. As ectothermic animals, salmon relies entirely on the surrounding water temperature to regulate metabolic processes. Consequently, even small deviations from optimal thermal ranges have direct and measurable impacts on enzymatic activity, feed conversion, immune competence, stress response, and developmental processes such as smoltification (Elliott & Elliott, 2010; Handeland et al., 2004).

Metabolic rate in salmon increases exponentially with temperature within the species' thermal tolerance range. This relationship is governed by temperature-dependent enzymatic reactions (Q10 effect), where biochemical reaction rates approximately double for every 10 °C increase. While moderate increases in temperature accelerate growth by enhancing digestion and metabolic turnover, temperatures above optimal thresholds increase oxygen demand beyond what the gills can efficiently supply, leading to physiological stress and reduced performance (Brett, 1971; Elliott & Elliott, 2010).

Feed intake, digestion speed, and nutrient assimilation are tightly linked to temperature. At optimal temperatures (generally 7-10 °C for parr and smolts), salmon exhibit maximum appetite and feed conversion efficiency. At lower temperatures, digestive processes slow, reducing growth rates. At higher temperatures (>18 °C), appetite declines sharply despite increased metabolic demand, leading to poor feed conversion ratios (FCR) and reduced growth (Handeland et al., 2008; Jobling, 2012).

As temperature rises, the solubility of oxygen in water decreases while the fish's oxygen requirement increases. This creates a physiological bottleneck where aerobic metabolism becomes limited, predisposing fish to hypoxia, stress, and disease susceptibility even when dissolved oxygen levels appear acceptable by standard measurement (Barton, 2002; Olsvik et al., 2013).

Chronic exposure to suboptimal temperatures suppresses immune function. Elevated temperatures increase susceptibility to bacterial pathogens such as *Aeromonas*, *Flavobacterium*, and *Renibacterium*, while low temperatures prolong disease progression by slowing immune responses and healing processes (Austin & Austin, 2016; Bowden, 2008). Many disease outbreaks in aquaculture coincide with seasonal temperature transitions rather than solely pathogen presence.

Temperature is a key environmental cue regulating smoltification. Seasonal increases in temperature, combined with photoperiod changes, stimulate endocrine pathways involving cortisol, thyroid hormones, and growth hormones that drive the parr-to-smolt transformation. Improper temperature regimes during this period can delay or desynchronize smoltification, producing physiologically unprepared smolts with poor seawater survival (McCormick et al., 2013; Stefansson et al., 2008).

Temperatures outside the optimal range induce chronic stress responses via activation of the hypothalamic–pituitary–interrenal (HPI) axis and cortisol release. Prolonged exposure leads to reduced growth, impaired osmoregulation, behavioural changes, and increased mortality. Behavioral indicators such as reduced swimming, surface aggregation, and increased aggression are often early signs of thermal stress (Ashley, 2007; Barton, 2002).

Based on our research, the indicator is scored in 4 levels. 7-10 °C – 1, 10-15 °C – 2, 16-17 °C-3, 3-6 °C – 4, where level 1 is the most optimal level for our rearing purposes and level 4 is the most suboptimal one.

WF calculation – suboptimal water temperatures can lead to illness -3, reduced survival -3, avoidance -1, and negative performance – 1. Optimal water quality increases natural behaviour +1 and supports positive performance +2 giving us a (WF=(2+1)-(-3-3-1-1)=11)

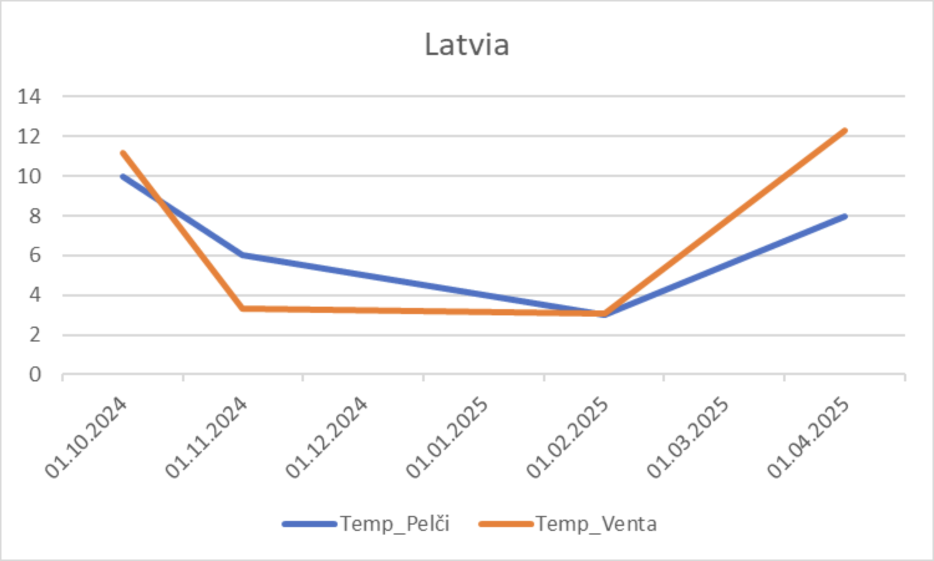


Fig. 1 Water temperature comparison of Venta River and fish farm “Pelči” rearing system

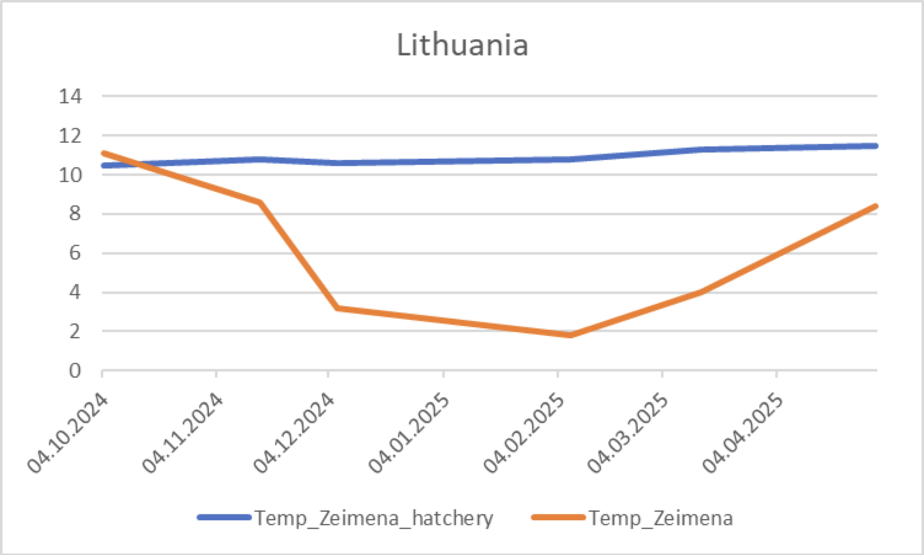


Fig. 2 Water temperature comparison of the river Zeimena and fish farm "Zeimena" rearing system.

Oxygen

Dissolved oxygen (DO) is the primary limiting factor in intensive salmon aquaculture because it directly governs aerobic metabolism, energy production, growth, immune function, and survival. Atlantic salmon are highly aerobic fish with substantial oxygen demands due to their active swimming behaviour, high metabolic rate, and large gill surface area specialized for rapid gas exchange. Even moderate reductions in oxygen availability rapidly affect physiological performance and welfare (Brett, 1971; Barton, 2002).

Oxygen is required for oxidative phosphorylation in mitochondria, where the majority of ATP is produced. When oxygen availability declines, salmon shift toward anaerobic metabolism, leading to lactate accumulation, metabolic acidosis, and reduced energy efficiency. This transition impairs growth, muscle performance, and recovery from stress (Brett, 1971; Farrell & Richards, 2009).

Feed intake and feed conversion efficiency are tightly linked to oxygen availability. Hypoxic conditions cause an immediate reduction in appetite and digestive efficiency. Even before visible behavioural signs occur, suboptimal DO reduces nutrient assimilation and increases feed conversion ratios (FCR). Many cases of poor growth performance in aquaculture are linked to chronic mild hypoxia rather than nutritional deficiencies (Jobling, 2012; Remen et al., 2016).

Oxygen requirements increase with temperature due to elevated metabolic rates, while oxygen solubility in water simultaneously decreases. This inverse relationship creates a physiological constraint where fish are most susceptible to hypoxia during warm periods, even when DO measurements appear acceptable. Therefore, oxygen management must always be considered in relation to temperature (Elliott & Elliott, 2010; Olsvik et al., 2013).

Low oxygen conditions force salmon to increase ventilation rates, which mechanically stresses gill tissues. Prolonged hyperventilation contributes to gill epithelial hyperplasia, increased mucus production, and susceptibility to bacterial gill disease and flavobacteriosis. As gill integrity declines, oxygen uptake efficiency worsens, creating a self-reinforcing cycle of respiratory stress (Austin & Austin, 2016; Roberts & Powell, 2003).

Chronic exposure to reduced DO suppresses immune responses through cortisol-mediated stress pathways. Hypoxic fish show increased susceptibility to opportunistic pathogens such as *Aeromonas*, *Flavobacterium*, and *Saprolegnia*. Disease outbreaks frequently coincide with periods of poor oxygenation, especially in high-density systems (Barton, 2002; Bowden, 2008).

Behavioral changes are early indicators of oxygen deficiency. Fish exposed to hypoxia exhibit reduced swimming activity, aggregation near water inlets, surface piping, and increased aggression. These behaviours are widely used as welfare indicators during inspections and routine farm assessments (Ashley, 2007; Noble et al., 2018).

In both RAS and flow-through systems, the maximum safe stocking density is determined primarily by how much oxygen can be delivered and distributed per unit time rather than by tank volume. Oxygen delivery capacity defines the biological carrying capacity of the system (Ellis et al., 2008; Remen et al., 2016).

Smoltification is an energetically demanding developmental stage requiring elevated metabolic activity and efficient osmoregulatory function. Inadequate oxygen during this period impairs gill Na^+/K^+-ATPase activity, disrupts hormonal regulation, and produces poor-quality smolts with reduced seawater survival (McCormick, 2001; Stefansson et al., 2008).

For Atlantic salmon in freshwater rearing systems:

- Optimal: >85–90% saturation
- Reduced performance begins: <80% saturation
- Chronic stress and disease risk: <70% saturation
- Acute mortality risk: <50–60% saturation

These values vary by life stage and temperature but are widely recognized in salmon aquaculture practice (Remen et al., 2016).

In our research, we found that adequate oxygen (above 80%) is a good indicator of sufficient dissolved oxygen levels in salmon rearing. For this reason, a scoring of >80% - 1, 70-80% - 2, 60-70% - 3, <60% - 4 was chosen. Poor oxygen saturation can lead to illness -3, reduced survival -3, abnormal behaviour -1, and negative performance -2. An optimal oxygen saturation in the water increases demand +1, increases natural behaviour +2 and it increases positive performance +2, giving us a WF of 14.

Water flow rate

Water flow rate is a critical physical parameter in both Recirculating Aquaculture Systems (RAS) and flow-through systems for salmon. It directly influences salmon physiology, behavior, welfare, and growth (Gomes et al., 2025; Timmerhaus et al., 2021).

In their natural habitat, salmon spend most of their time swimming against a current. This continuous aerobic swimming promotes the development of red (oxidative) muscle fibres, strengthens the heart, and improves overall swimming capacity. In captive systems, providing a suitable water velocity stimulates a similar pattern of sustained swimming (Nilsen et al., 2018; Gomes et al., 2025). This results in:

- increased aerobic muscle development
- improved cardiac performance
- better body conformation and reduced fat deposition

Insufficient current leads to lethargy, muscle underdevelopment, and reduced physical fitness, while excessive current can induce fatigue and suppress growth because too much energy is expended on swimming rather than on tissue development (Solstorm et al., 2016; Timmerhaus et al., 2021).

Swimming against a current increases metabolic demand and oxygen consumption. A moderate current promotes an optimal metabolic rate that supports efficient feed utilization and growth (Agbeti et al., 2024; Waldrop et al., 2018). When current speed is too low, salmon become under-stimulated, reducing their metabolic activity and feed intake, which can lead to poorer growth efficiency. In contrast, if currents are too strong, fish divert excessive energy into locomotion, resulting in reduced growth despite adequate feeding (Solstorm et al., 2016). Thus, the correct current speed balances energetic expenditure with efficient energy conversion into growth.

A consistent directional flow naturally aligns salmon into a stable schooling formation. This has multiple welfare benefits:

- reduced aggression and territorial behaviour
- better social cohesion

- predictable swimming patterns that reduce stress
- prevention of fin nipping and distribution conflicts around feeders

When flow is insufficient, fish may disperse randomly within the tank, leading to dominance hierarchies, increased stress responses, and more frequent aggressive interactions (Solstorm et al., 2016). Proper current speed therefore promotes behavioural stability and reduces chronic stress.

Current speed plays a major role in the distribution of oxygen, the removal of metabolic waste, and the overall hydrodynamic efficiency of the system. Adequate flow ensures:

- uniform oxygen concentration throughout the tank
- efficient dispersion of CO_2 and other dissolved wastes
- continuous suspension of solid particles so they can be transported to filtration units (in RAS)
- minimization of localized “dead zones” with low oxygen and high waste accumulation

Inadequate current can lead to pockets of poor water quality which negatively affect fish health, gill condition, and pathogen susceptibility (Timmerhaus et al., 2021).

Smoltification is associated with changes in behaviour and physiology that prepare juvenile salmon for downstream migration and transition into seawater. Water current acts as an environmental cue that promotes:

- orientation in the direction of flow
- increased swimming endurance
- stimulation of osmoregulatory development (e.g., gill Na^+/K^+-ATPase activity)
- improved readiness for seawater entry

Proper current speed ensures that fish develop the stamina and physiological robustness needed for the smolt stage.

In both RAS and flow-through systems, solid waste can settle if water movement is insufficient. Accumulated organic matter creates microbial hotspots that:

- decrease oxygen availability
- increase ammonia production
- promote pathogenic bacteria
- elevate disease risk

By maintaining adequate current speed, waste is continuously carried to the outflow or mechanical filters, keeping the environment clean, and reducing health problems (Timmerhaus et al., 2021).

Our personal research shows that a regular current speed of 0.2 m/s is sufficient and necessary for adequate fish welfare so a scoring of 0,2 m/s – 1, >0,2 m/s – 2, <0,2 m/s – 3 has been chosen for our purposes.

WF - Increase or decrease in water flow rate can increase health problems –3, cause abnormal behaviour -2, reduce survivability -3, induce avoidance -1 and increase negative performance -1. A optimal water flowrate of 0.2 m/s can increase natural behaviour +1 and positive performance +2 giving us a WF of 13.

Stocking density

Stocking density in salmonid aquaculture is extremely important because it directly affects fish welfare, water quality, and production performance (Liu et al., 2018; RWTH Aachen University, 2024).

In recirculating aquaculture systems (RAS) especially, high stocking densities increase metabolic waste production, including ammonia, carbon dioxide (CO_2), and suspended solids. If filtration, oxygenation, CO_2 removal, and solids management are insufficient, water quality may deteriorate, negatively affecting growth, immune function, and overall fish health (Liu et al., 2018; Roque d’Orbcastel et al., 2009).

More fish per unit volume requires greater oxygen supply. Aquaculture systems must therefore ensure sufficient oxygen saturation and efficient gas exchange. In flow-through systems, water renewal must maintain adequate oxygen levels for fish metabolism and welfare. Regulatory frameworks may specify minimum acceptable oxygen levels or density limits to protect fish welfare (European Commission, 2020).

High stocking densities can also impair normal swimming behaviour, increase physiological stress responses, reduce growth performance, and negatively affect immune function (Li, 2016; Liu et al., 2018). Behavioural disturbances and increased competition for space may also contribute to reduced welfare and increased susceptibility to disease.

The sustainable stocking density of a system depends on multiple technical and biological factors. Tank geometry, water flow rates, filtration capacity, oxygenation systems, waste removal efficiency, and the life stage of the fish all influence the maximum density that can be safely maintained (RWTH Aachen University, 2024; Nofima Centre for Recirculation in Aquaculture, n.d.).

Our research showed that stocking densities tend to vary depending on the salmonid growing stage and the system in which you are growing the fish. Parr can be stocked more densely than pre-smolts or smolts. Taking into account the deviations we determined that an optimal stocking density of 19 kg/m^3 is required for efficient salmon rearing so we used a scoring system of 1-19 kg/ m^3 – 1, 19,1-25 kg/ m^3 – 2, 25,1-38 kg/ m^3 – 3, 38+ kg/ m^3 – 4.

WF – a stocking density exceeding the optimal 19 m^3 can lead to multiple disorders like illness -2, reduced survival –2, abnormal behaviour –1, aggression –1, frustration –1, negative performance –1. An appropriet stocking density increases natural behaviour +1, positive performance +1, and demand +1, giving us a WF of 11.

Lighting

Lighting is a major environmental regulator of physiological development, behaviour, growth, and welfare in Atlantic salmon aquaculture. Unlike temperature and oxygen, which influence metabolic processes directly, light primarily acts through neuroendocrine pathways that regulate circadian rhythms, seasonal development, feeding behaviour, and smoltification. Both photoperiod (day length) and light intensity must be carefully managed in hatcheries, flow-through systems, and RAS to ensure normal development and optimal performance (Boeuf & Le Bail, 1999; Handeland et al., 2008).

Atlantic salmon use changes in day length as a primary environmental cue for seasonal physiological transitions. Increasing photoperiod in spring stimulates endocrine pathways involving melatonin suppression, increased growth of hormone secretion, thyroid hormone activity, and cortisol release, all of which are necessary to initiate smoltification. Artificial manipulation of photoperiod is widely used in aquaculture to control the timing of smolt development, but incorrect regimes can desynchronize or impair this process (Stefansson et al., 2008; McCormick et al., 2013).

Light exposure regulates circadian rhythms through melatonin production in the pineal gland. Disruption of normal light–dark cycles alters feeding rhythms, stress hormone release, and metabolic regulation. Continuous light (24L:0D), commonly used to stimulate growth, suppresses melatonin production and can lead to chronic stress, reduced welfare, and altered behaviour if applied inappropriately or for prolonged periods (Boeuf & Le Bail, 1999; Iigo & Aida, 1995).

Light intensity and photoperiod directly influence feeding behaviour. Salmon are visual feeders, and insufficient light reduces feed detection and intake. Conversely, excessive light intensity can cause stress, increased aggression, and avoidance behaviour. Optimal light conditions improve appetite, growth rate, and feed conversion efficiency (Jobling, 2012; Handeland et al., 2008).

Smoltification is strongly dependent on the interaction between photoperiod and temperature. Increasing day length is required to activate hormonal pathways that upregulate gill Na⁺/K⁺-ATPase activity, enabling osmoregulation in seawater. Inadequate or mistimed light regimes produce incomplete smoltification, resulting in poor seawater adaptation, increased stress, and higher post-transfer mortality (McCormick, 2001; Stefansson et al., 2008).

Lighting influences swimming behaviour, schooling, aggression, and spatial distribution within tanks. Poor lighting conditions may lead to increased fin damage, uneven growth, and social stress. Continuous or inappropriate lighting has been associated with increased incidence of deformities and welfare problems in juvenile salmon (Ashley, 2007; Noble et al., 2018).

Typical hatchery and RAS practices include:

- Parr stage: 12L:12D to support normal development
- Pre-smolt phase: Gradual increase to simulate spring photoperiod
- Smolt production: Controlled long-day photoperiod (16–24L) to initiate smoltification
- Light intensity: Moderate, evenly distributed illumination to support feeding without causing stress

These regimes must be synchronized with temperature and developmental stage for effective results (Handeland et al., 2008). For this reason we decided to value lighting as optimal or suboptimal.

WF- suboptimal lighting can cause a variety of issues with illnesses –1, frustration –1 and negative performance –2, with the optimal lighting increasing positive performance +1 and antural behaviour +1, giving us a total value of 6.

Stress

Stress in Atlantic salmon (*Salmo salar*) is a physiological and behavioural response to environmental or husbandry challenges that disrupt homeostasis. In aquaculture, common stressors include handling, crowding, transport, low dissolved oxygen, sub-optimal temperatures, and poor water quality. These stressors activate the hypothalamic–pituitary–interrenal (HPI) axis, resulting in cortisol release and secondary metabolic changes that influence growth, immune competence, gut integrity, and welfare (Barton, 2002; Sundh et al., 2010).

The primary stress response in salmon involves activation of the HPI axis and the release of cortisol. Cortisol mobilizes energy reserves by increasing plasma glucose and altering metabolic priorities to cope with acute challenges. While adaptive in the short term, prolonged cortisol elevation leads to negative physiological consequences such as reduced growth efficiency and immune suppression (Barton, 2002; Iwama et al., 2011).

Secondary stress indicators include elevated plasma glucose and lactate levels, reflecting increased metabolic demand and anaerobic metabolism during acute stress events (Barton, 2002).

Chronic stress has been shown to impair intestinal barrier integrity in Atlantic salmon. Salmon reared in typical sea-cage environments exhibited reduced intestinal electrical resistance and increased permeability, which were linked to elevated cortisol levels. This demonstrates that prolonged environmental stress directly affects nutrient absorption and disease resistance (Sundh et al., 2010).

Additionally, chronic exposure to hypoxia and temperature stress alters gene expression related to metabolism, oxidative stress, and cellular repair mechanisms, indicating long-term physiological strain (Olsvik et al., 2013).

Handling, grading, crowding, and transport are unavoidable parts of aquaculture but are significant acute stressors. These events cause rapid increases in cortisol, glucose, and lactate, and alter behaviour and cardiovascular responses (Barton, 2002; Iwama et al., 2011). Temperature outside the species-specific optimum and low dissolved oxygen act synergistically as stressors. As temperature rises, metabolic oxygen demand increases while oxygen solubility decreases, intensifying physiological stress. Long-term exposure leads to metabolic depression and reduced growth performance (Olsvik et al., 2013).

Not all stress is bad. For this reason, we scored stress in 3 forms: eustress, average levels of stress, distress.

WF – chronic elevated stress levels can increase possibility of illness development –3, reduce survival –2, induce abnormal behaviour –2, increase frustration –1 and induce negative performance –1. Eustress can increase natural behaviour +1 and positive performance +1, giving us a total WF of 11.

Mortality

Mortality is a key performance and welfare indicator in Atlantic salmon (*Salmo salar*) aquaculture. Elevated mortality rates are rarely caused by a single factor; instead, they typically result from the interaction of environmental stressors, infectious disease, husbandry practices, and physiological vulnerability during sensitive life stages such as smoltification and sea transfer (Ellis et al., 2012; Noble et al., 2018).

Monitoring mortality patterns provides important diagnostic insight into underlying welfare problems, water quality issues, and disease outbreaks in both recirculating aquaculture systems (RAS) and flow-through systems.

Environmental parameters such as dissolved oxygen, temperature, ammonia, carbon dioxide, and stocking density directly influence survival. Hypoxia, elevated temperatures, and poor water quality impair aerobic metabolism and increase physiological stress, which can lead to mortality directly or indirectly by increasing susceptibility to disease (Portz et al., 2006; Person-Le Ruyet et al., 2008).

Temperature is particularly critical because metabolic oxygen demand rises with temperature while oxygen solubility declines. Exposure to sub-optimal temperatures over prolonged periods has been linked to increased mortality and reduced disease resistance in salmonids (Elliott & Elliott, 2010).

In intensive salmon rearing, infectious diseases are among the most common direct causes of mortality. Bacterial diseases such as furunculosis (*Aeromonas salmonicida*), bacterial kidney disease (*Renibacterium salmoninarum*), and flavobacteriosis, as well as fungal infections like saprolegniosis, often occur when fish are immunocompromised due to stress or poor environmental conditions (Austin & Austin, 2016).

Chronic stress suppresses immune function through prolonged cortisol elevation, reducing the fish's ability to resist pathogens and increasing outbreak severity and mortality rates (Barton, 2002).

Certain life stages show increased mortality risk:

- Smoltification — physiological transformation increases vulnerability to osmotic and environmental stress (McCormick et al., 2013).
- Parr stage — higher sensitivity to water quality fluctuations and pathogens (Noble et al., 2018).

Mortality events often cluster around these transition periods.

Handling, grading, crowding, and transport are significant mortality risk factors if not carefully managed. Acute stress from these events can cause immediate mortality or delayed mortality through secondary infections and physiological collapse (Ashley, 2007; Portz et al., 2006).

High stocking densities exacerbate these effects by increasing competition for oxygen, elevating waste metabolite concentrations, and facilitating pathogen transmission.

Mortality is not only a production metric but also a welfare indicator. Sudden increases in daily mortality often signal:

- Oxygen depletion
- Toxic metabolite buildup (ammonia, CO_2)

- Disease outbreak
- Severe stress events

Routine mortality tracking, combined with water quality and behavioural observations, is essential for early problem detection in salmon farms (Ellis et al., 2012).

Patterns such as chronic low-level mortality versus acute mortality spikes provide different diagnostic clues for farm managers and veterinarians.

We valued mortality as insignificant when 0-2 fish died per week, so the scoring we agreed upon was 0 – 2 fish per week – 1, 3-10 – 2, >10 – 3.

WF – When describing mortality, we usually notice an increase in illness –3, pain –2, reduction in survival –3 and a negative performance of –2. A low mortality level increases positive performance +1, giving us a total of 11.

Body condition

Body condition is a widely used indicator of nutritional status, health, and welfare in Atlantic salmon (*Salmo salar*) aquaculture. It reflects the relationship between fish weight and length and provides insight into energy reserves, growth efficiency, feeding success, and the presence of chronic stress or disease. Poor body condition is often one of the earliest measurable signs that rearing conditions, nutrition, or health status are sub-optimal (Bolger & Connolly, 1989; Noble et al., 2018).

In salmon farming, body condition is not only a production metric but also a welfare indicator, as it integrates the cumulative effects of environmental quality, stocking density, oxygen availability, disease burden, and feeding regimes.

Fulton’s Condition Factor (K)

The most applied metric for assessing body condition in salmonids is **Fulton’s condition factor (K)**:

$$K = 100\,\frac{W}{L^3}$$

Where W is body weight (g) and L is length (cm).

This index assumes isometric growth and provides a rapid, non-invasive method to compare the “plumpness” or robustness of fish within and between populations (Bolger & Connolly, 1989). Changes in K over time can indicate alterations in feeding efficiency, stress exposure, or disease progression.

Good body condition reflects:

- Adequate feed intake and nutrient utilization
- Optimal environmental conditions (oxygen, temperature, water quality)
- Low chronic stress exposure

Conversely, reductions in condition factor are associated with chronic stress, hypoxia, high stocking densities, or subclinical disease, where energy is diverted from growth toward maintenance and stress responses (Ashley, 2007; Barton, 2002).

Environmental stressors such as low dissolved oxygen and sub-optimal temperatures reduce appetite and feed conversion efficiency, which directly affects body condition (Elliott & Elliott, 2010).

Fish in poor body condition are more susceptible to infectious diseases. Chronic stress and inadequate nutrition suppress immune function, increasing vulnerability to bacterial and fungal pathogens common in aquaculture systems (Barton, 2002; Austin & Austin, 2016).

Body condition is therefore often used by veterinarians and farm managers as an early warning sign before overt clinical disease or increased mortality occurs.

Body condition is included among recommended welfare indicators for farmed Atlantic salmon because it is:

- Easy to measure during routine sampling
- Non-lethal and minimally invasive
- Reflective of long-term rearing conditions rather than acute events

Noble et al. (2018) identify body condition as a key operational welfare indicator that should be monitored alongside mortality, behaviour, and water quality parameters.

Although widely used, Fulton’s condition factor assumes isometric growth and may be influenced by life stage (e.g., smoltification), gonadal development, and body shape changes. Therefore, it should be interpreted alongside other indicators such as growth rate, feed conversion ratio, and health observations (Bolger & Connolly, 1989). As an appropriate body condition (Fulton’s condition factor), we scored it >1,1 – 1, 0,9-1,1 – 2, <0,9 – 3.

WF – a decrease in body condition can increase the development of illness –2, reduce survival -1, increase abnormal behaviour –1, increase negative performance –1 and incrase frustration –1. An optimal body condition increases positive performance +1 and improves natural behaviour +1, giving us a total WF of 8.

Spinal deformities

Spinal deformities are among the most common skeletal abnormalities observed in farmed Atlantic salmon (*Salmo salar*). These deformities include lordosis, kyphosis, scoliosis, vertebral compression, and vertebral fusion. They represent a significant welfare concern and production issue because they impair swimming performance, feeding efficiency, growth, and market quality (Fjelldal et al., 2012; Witten et al., 2009).

Skeletal deformities are multifactorial in origin and are associated with interactions between genetics, nutrition, environmental conditions, and husbandry practices during sensitive developmental stages.

Proper vertebral development in salmon depends on adequate mineralization, particularly involving phosphorus, calcium, and vitamin D metabolism. Nutritional imbalances during early life stages, especially phosphorus deficiency, have been strongly linked to vertebral deformities and reduced bone mineralization (Fjelldal et al., 2009; Witten et al., 2009).

Rapid growth rates promoted by intensive feeding regimes can outpace proper skeletal mineralization, increasing the risk of deformity when mineral supply or environmental conditions are suboptimal (Fjelldal et al., 2012).

Environmental factors such as temperature, water current velocity, and stocking density influence skeletal development. Elevated temperatures during early development accelerate growth but may impair correct vertebral formation and mineralization, leading to increased deformity incidence (Wargelius et al., 2005).

Insufficient water current in tanks reduces swimming activity, which is necessary for normal musculoskeletal development. Conversely, appropriate sustained swimming activity has been shown to improve vertebral strength and reduce deformity prevalence (Totland et al., 1987; Fjelldal et al., 2012).

High stocking densities may further exacerbate these issues by limiting movement and increasing chronic stress, indirectly affecting skeletal development.

Spinal deformities impair swimming ability and increase energy expenditure during locomotion. Affected fish often show reduced competitive ability during feeding and are more susceptible to chronic stress and secondary disease due to reduced physiological performance (Ashley, 2007; Fjelldal et al., 2012).

Severe deformities may lead directly to culling or mortality due to inability to compete for feed or maintain normal posture.

The risk of vertebral deformities is highest during:

- Parr stages when ossification is ongoing
- Periods of rapid growth
- Smoltification, when major physiological restructuring occurs

During these stages, the balance between growth rate, mineral availability, and environmental conditions is especially important (Witten et al., 2009).

Because spinal deformities result from long-term suboptimal rearing conditions, they are considered a chronic welfare indicator. Their presence in a population often reflects historical issues with nutrition, water quality, temperature control, or tank hydraulics (Noble et al., 2018).

Regular monitoring of deformity prevalence is therefore recommended as part of welfare assessment protocols in salmon aquaculture. In our research we examined multiple fish for scoliosis and noted the pathology if it was present, or scoring this indicator as not present – 1, present – 2.

WF - if scoliosis is present, it serves as evidence of health problems and we score it as –2, it drastically reduces survival rate –2, increases frustration –1 and increases negative performance –2. No visible scoliosis, in return, shows us that fish are free to express natural behaviour +1 and increase demand and positive performance, both +1, respectively. Giving us a total WF of 10.

Smoltification

Smoltification is a complex developmental transformation that prepares juvenile Atlantic salmon (*Salmo salar*) for the transition from freshwater to seawater. This process involves coordinated morphological, physiological, behavioural, and endocrine changes that enable the fish to achieve seawater tolerance through effective osmoregulation. In aquaculture, successful smoltification is critical because incomplete or poorly timed smolt development is strongly associated with stress, disease susceptibility, poor growth after sea transfer, and increased mortality (McCormick et al., 2013; Stefansson et al., 2008).

Smoltification is regulated by endocrine changes involving increased secretion of growth hormone, cortisol, and thyroid hormones. These hormones stimulate the development of seawater ion-regulatory mechanisms, particularly in the gills, where there is increased activity of Na^+/K^+-ATPase and differentiation of chloride cells necessary for salt excretion in seawater (McCormick, 2001; Evans et al., 2005).

This physiological shift allows the fish to move from actively absorbing ions in freshwater to actively excreting excess salts in seawater.

During smoltification, salmon undergo visible morphological changes:

- Silvering of the body due to guanine deposition in scales
- Darkening of fin margins
- Streamlined body shape
- Increased schooling behaviour and downstream migratory drive

These changes are reliable external indicators of internal physiological readiness for seawater (Stefansson et al., 2008).

Smoltification is strongly influenced by environmental cues, primarily photoperiod and temperature. Increasing day length in spring is the primary trigger for endocrine changes initiating smolt development. Temperature modulates the rate and success of the process; deviations from optimal temperature ranges can delay or disrupt smoltification (Handeland et al., 2004).

In aquaculture, artificial photoperiod manipulation is commonly used to control the timing of smolt production, but incorrect light or temperature regimes can result in incomplete smolt development and poor seawater performance.

Gill Na^+/K^+-ATPase activity is widely used as a quantitative indicator of smolt status. Peak enzyme activity corresponds to maximum seawater readiness, and declining activity indicates desmoltification, where the fish loses seawater tolerance if transfer is delayed (McCormick, 2001).

This is a critical management consideration in hatcheries and RAS systems.

Fish transferred to seawater before full smolt development experience:

- Osmoregulatory failure
- Elevated cortisol and stress responses
- Reduced appetite and growth
- Increased susceptibility to disease
- Elevated post-transfer mortality

Thus, improper smolt timing is one of the most important hidden causes of mortality and poor performance in salmon aquaculture (Stefansson et al., 2008; McCormick et al., 2013).

Because smoltification integrates environmental conditions, endocrine status, and physiological readiness, it is considered a key welfare and quality indicator in salmon production. Monitoring morphological signs, gill enzyme activity, condition factor, and behaviour allows farmers to determine optimal transfer timing and reduce stress-related losses (Noble et al., 2018).

While scoring smoltification we decided that a level score of Smolt – 1, presmolt – 2, parr – 3 is more than adequate for our restocking purposes.

WF – Since smoltification is a morphological indicator of physical maturity and readiness for the sea a salmonid that has not reached the smoltification stage can have a reduced survival rate –2, increase in frustration –1 and aggression –1, and a negative performance –1. A fully developed smolt has a positive performance +1, increased demand +1 and a increase in natural behaviour expression +1. Giving us a total WF of 8.

Fin necrosis

Fin necrosis (often referred to as fin erosion or fin rot) is a common external pathology observed in farmed Atlantic salmon (*Salmo salar*). It is characterized by fraying, whitening, tissue loss, inflammation, and progressive degradation of fin margins. Although not always immediately lethal, fin necrosis is a significant welfare indicator because it reflects chronic environmental stress, suboptimal husbandry, and increased susceptibility to opportunistic infections (Ellis et al., 2008; Noble et al., 2018).

Fin condition is therefore widely used in welfare assessment protocols for salmon aquaculture.

Fin necrosis is typically multifactorial and associated with:

- High stocking densities
- Mechanical abrasion (tank walls, fish contact)
- Poor water quality (elevated ammonia, CO_2, low oxygen)
- Chronic stress
- Opportunistic bacterial infection (e.g., *Flavobacterium*, *Aeromonas*, *Pseudomonas*)

Under intensive rearing conditions, fins are particularly vulnerable because they are thin, highly vascularized tissues exposed directly to the environment (Turnbull et al., 1998; Ellis et al., 2008).

High stocking density increases physical contact between fish and promotes aggressive interactions such as fin nipping. Studies have demonstrated a clear relationship between stocking density and fin damage prevalence, particularly affecting the dorsal and caudal fins (Turnbull et al., 1998).

Crowding also elevates chronic stress levels, which reduces tissue repair capacity and immune defence, allowing minor abrasions to progress into necrotic lesions (Barton, 2002).

Poor water quality contributes significantly to fin degradation. Elevated ammonia, carbon dioxide, and suspended solids irritate delicate fin tissues and impair healing. Low dissolved oxygen further compromises tissue repair by limiting aerobic metabolism necessary for regeneration (Ashley, 2007).

In RAS and flow-through systems, inadequate hydraulics and water exchange can therefore indirectly promote fin necrosis.

While fin necrosis often begins as mechanical or environmental damage, opportunistic bacteria frequently colonize damaged tissue, worsening the lesion. Species of *Flavobacterium*, *Aeromonas*, and *Pseudomonas* are commonly isolated from affected fins (Austin & Austin, 2016).

Thus, fin necrosis is often both a welfare issue and a precursor to infectious diseases.

Because fin damage develops over time under chronic suboptimal conditions, it is considered a long-term welfare indicator rather than a sign of acute stress. Noble et al. (2018) include fin condition scoring among recommended operational welfare indicators for Atlantic salmon farms.

Routine visual scoring of dorsal, pectoral, abdominal, anal and caudal fins provide a simple, non-invasive method to assess rearing quality.

Fish with severe fin necrosis exhibit:

- Reduced swimming efficiency
- Increased energy expenditure
- Lower competitive ability during feeding
- Greater susceptibility to systemic infection

In severe cases, fin necrosis may contribute indirectly to increased mortality due to secondary disease or chronic stress (Ellis et al., 2008).

For this reason, while scoring fin damage we used a scoring system of 0-25% - 1, 25-50% - 2, 50- 100% - 3, where the % mentioned is the % of fin damaged by infection or other sources.

WF – Calculating the WF for fin necrosis gives us an increase in illness –3, patients with fin necrosis also can develop pain –3, gradual progression of the infection can cause reduction in survival rates –3, loss of fins can induce abnormal behaviour –1 and induce negative performance –2. Healthy fins, in return, increase natural behaviour +1 and positive performance +1, giving us a total WF of 14.

Operculum necrosis

Operculum necrosis is a pathological condition affecting the gill cover (operculum) in farmed Atlantic salmon (*Salmo salar*). It is characterized by tissue erosion, ulceration, discoloration, and in severe cases, exposure to underlying gill structures. Although often non-lethal initially, operculum necrosis represents a significant welfare concern, as it reflects chronic stress, poor environmental quality, mechanical damage, or secondary infection (Austin & Austin, 2016; Ellis et al., 2008).

Operculum necrosis is generally multifactorial, with the following contributing factors:

- Mechanical trauma: Contact with tank walls, nets, or other fish during crowding and handling.
- Poor water quality: Elevated ammonia, CO_2, or low dissolved oxygen irritates delicate opercular tissues.
- Chronic stress: Cortisol-mediated suppression of tissue repair mechanisms allows small injuries to progress to necrosis.
- Opportunistic bacterial infections: Species such as *Flavobacterium*, *Aeromonas*, and *Pseudomonas* often colonize damaged tissue (Austin & Austin, 2016; Turnbull et al., 1998).

Chronic exposure to these factors results in progressive tissue loss and can compromise gill function.

High stocking density increases the likelihood of mechanical trauma to opercula, both through aggressive interactions and physical contact with tank infrastructure. Frequent handling, grading, or transport amplifies this risk (Barton, 2002; Ashley, 2007). Crowding-related stress also delays tissue regeneration and allows opportunistic bacteria to establish lesions.

Suboptimal water quality exacerbates operculum necrosis. Ammonia accumulation, elevated nitrite, high suspended solids, and hypoxia irritate the opercular epithelium, impair healing, and predispose tissue to secondary infection. Controlled water flow and oxygenation in recirculating systems or flow-through systems are therefore essential for minimizing risk (Ashley, 2007).

Operculum necrosis can directly impact:

- Gill function: Tissue loss can impair ventilation and gas exchange efficiency.
- Respiratory efficiency: Compromised opercula increase energy expenditure during respiration.
- Stress susceptibility: Fish with operculum lesions are more vulnerable to secondary infections.

- Feeding and growth: Lesions can indirectly reduce competitive ability and appetite (Ellis et al., 2008).

Because operculum necrosis develops under chronic environmental stress or suboptimal husbandry, it is considered a long-term welfare indicator.

Routine inspection of opercula during handling or sampling can detect early signs of necrosis. Preventive measures include:

- Optimizing water quality (oxygen, ammonia, nitrite, and CO_2 control)
- Minimizing mechanical trauma during handling and transport
- Reducing stocking density to limit aggressive interactions
- Prompt diagnosis and treatment of opportunistic bacterial infections (Austin & Austin, 2016; Turnbull et al., 1998)

Monitoring operculum condition alongside fin integrity, gill health, and body condition provides a comprehensive welfare assessment. For this reason, we decided to score opperculum necrosis as not present – 1, present – 2.

WF – Necrosis of the opperculum can induce a variety of illnesses, so we value it as –3, it can increase pain –2, reduce survival –2 and also induce negative performance –1. A healthy opperculum increases positive performance +1, giving us a total of 9.

Table 1. Welfare scoring

Welfare indicator	**Associated indicator level**	**Indicator score**
Water temperature	7-10 °C – 1, 10-15 °C – 2, 15-17 °C-3, 3-6 °C – 4	1 0,67 0,33 0
Oxygen saturation	>80% - 1, 70-80% - 2, 60-70% - 3, <60% - 4	1 0,67 0,33 0
Water flow rate	0,2 m/s – 1, >0,2 m/s – 2, <0,2 m/s – 3	1 0,5 0
Stocking density	1-19 kg/ m^3 – 1, 19-25 kg/ m^3 – 2, 25-38 kg/ m^3 – 3, >38 kg/ m^3 – 4	1 0,67 0,33 0
Lighting	Optimal – 1,	1

	suboptimal - 2	0
Stress	Eustress – 1, average stress – 2, distress – 3	1 0,5 0
Mortality	0 – 2 fish per week – 1, 3-10 – 2, >10 – 3	1 0,5 0
Body condition	>1,1 – 1, 0,9-1,1 – 2, <0,9 – 3	1 0,5 0
Spinal deformities	Not present – 1, present – 2	1 0
Smoltification	Smolt – 1, presmolt – 2, parr – 3	1 0,5 0
Fin necrosis	0-25% - 1, 25-50% - 2, 50- 100% - 3	1 0,5 0
Operculum necrosis	Not present – 1, present – 2	1 0

Table 2. Weighting category: Each weighting category receives a weighting score. The weighing scores are expert’s opinions suited for our intents in the project. Adapted from Pettersen et al. (2013)

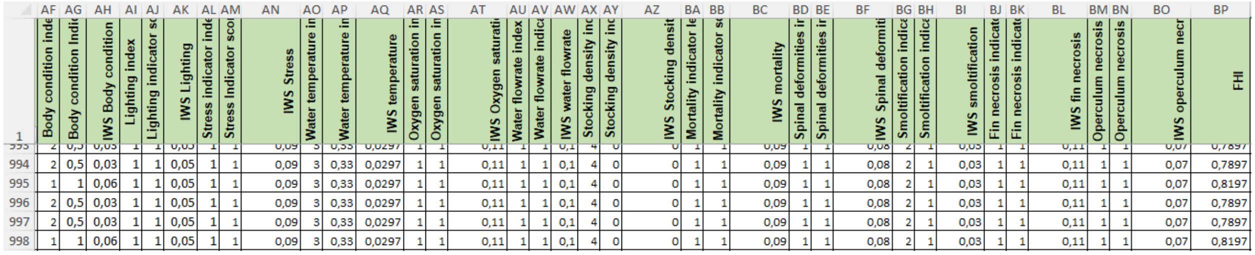
Weighting category	Brief description	Range of WS
Illness	Evidence of health problems, including increased mortality, but excluding skin lesions, fin damage and abnormalities in body shape (see ‘pain’).	-5 to -1
Pain	Evidence of unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage	-5 to -1
Reduced survival	Evidence of reduced survival related to physiological requirements (other than through specific health problems), for example, longevity, deprivation of food, poor environment	-5 to -1

Abnormal behaviour	Evidence of disturbed behaviour and/or apathy.	-3 to -1
Aggression	Aggression Evidence of aggression such as bite marks and attacks.	-3 to -1
Avoidance	Avoidance Evidence of avoiding stimuli (which are perceived as dangerous/noxious).	-3 to -1
Frustration	Frustration Evidence of blocked behaviour or deprivation.	-3 to -1
Negative performance	Evidence of decreased performance (that is likely to indicate negative affect), including reproduction effects, but excluding specific survival aspects related to physiological necessities and illness.	-3 to -1
Demand	Demand Evidence that the fish are willing to spend effort to obtain food or other recourses.	1-5
Natural behaviour	Natural behaviour Evidence of (potential positive reward from) behaviour as seen in (semi) natural conditions.	1-3
Positive performance	Positive performance Evidence of healthy, fit fish, which are growing well.	1-3

Table 3. Scoring of weighing factors

Welfare indicator	**Weighting factor (WF)**	**Relative weighting factor (RWF)**	**Indicator scores (IS)**
Water temperature	11	0.09	1 0.67 0.33 0
Oxygen saturation	14	0.11	1 0.67 0.33 0
Water flow rate	13	0.10	1 0,5 0
Stocking density	11	0.09	1

			0.67 0.33 0
Lighting	6	0.05	1 0
Stress	11	0.09	1 0.5 0
Mortality	11	0.09	1 0.5 0
Body condition	8	0.06	1 0.5 0
Spinal deformities	10	0.08	1 0
Smoltification	8	0.06	1 0.5 0
Fin necrosis	14	0.11	1 0.5 0
Operculum necrosis	9	0.07	1 0
SUM	126	1	1 0



	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP
1	Body condition inde	Body condition Indi	IWS Body condition	Lighting index	Lighting indicator sc	IWS Lighting	Stress indicator inde	Stress Indicator sco	IWS Stress	Water temperature in	Water temperature in	IWS temperature	Oxygen saturation in	Oxygen saturation in	IWS Oxygen saturati	Water flowrate index	Water flowrate indica	IWS water flowrate	Stocking density inc	Stocking density inc	IWS Stocking densit	Mortality indicator le	Mortality indicator sc	IWS mortality	Spinal deformities ir	Spinal deformities ir	IWS Spinal deformiti	Smoltification indica	Smoltification indica	IWS smoltification	Fin necrosis indicato	Fin necrosis indicato	IWS fin necrosis	Operculum necrosis	Operculum necrosis	IWS operculum necr	FHI
994	2	0,5	0,03	1	1	0,05	1	1	0,09	3	0,33	0,0297	1	1	0,11	1	1	0,1	4	0	0	1	1	0,09	1	1	0,08	2	1	0,03	1	1	0,11	1	1	0,07	0,7897
995	1	1	0,06	1	1	0,05	1	1	0,09	3	0,33	0,0297	1	1	0,11	1	1	0,1	4	0	0	1	1	0,09	1	1	0,08	2	1	0,03	1	1	0,11	1	1	0,07	0,8197
996	2	0,5	0,03	1	1	0,05	1	1	0,09	3	0,33	0,0297	1	1	0,11	1	1	0,1	4	0	0	1	1	0,09	1	1	0,08	2	1	0,03	1	1	0,11	1	1	0,07	0,7897
997	2	0,5	0,03	1	1	0,05	1	1	0,09	3	0,33	0,0297	1	1	0,11	1	1	0,1	4	0	0	1	1	0,09	1	1	0,08	2	1	0,03	1	1	0,11	1	1	0,07	0,7897
998	1	1	0,06	1	1	0,05	1	1	0,09	3	0,33	0,0297	1	1	0,11	1	1	0,1	4	0	0	1	1	0,09	1	1	0,08	2	1	0,03	1	1	0,11	1	1	0,07	0,8197

Figure 3. Fish health index model (available in 3.2.1 deliverable)

Summary

This project presents the development of a structured Fish Health Index (FHI) Model designed to quantitatively evaluate the physiological condition and release readiness of juvenile salmon prior to introduction into natural environments. The model integrates biological measurements, developmental markers, and pathology indicators into a standardized, rule-based scoring framework.

The primary objective was to transform raw biometric and categorical health data into a coherent composite index that supports objective decision-making. Key input variables included smoltification stage, weight, length, and observed pathological conditions. These indicators were selected based on their biological relevance to growth performance, developmental status, and overall health stability during the critical transition phase to wild habitats.

Methodologically, the project applies a semantic modeling approach inspired by structured welfare assessment systems such as the Salmon Welfare Index Model (SWIM 1.0 & 2.0) (Stien et al., 2013; Petersen et al., 2014). Continuous and categorical measurements were converted into discrete health levels using conditional logic formulas implemented in Microsoft Excel. Nested IF functions and categorical mapping techniques were employed to classify indicator values into biologically meaningful ranges. Each level was then normalized into a standardized score (ranging from optimal to poor condition), enabling comparability across indicators.

The analytical workflow relied on:

- Microsoft Excel for rule-based classification, logical threshold modeling, and score aggregation
- Conditional formulas (IF logic) to operationalize health thresholds
- Weighted scoring structures to compute partial and total index values
- Structured data tables for transparent and reproducible calculations

The resulting Fish Health Index provides:

- A transparent and interpretable scoring mechanism
- A scalable evaluation framework applicable to different cohorts
- A practical decision-support tool for assessing fish release readiness
- A standardized methodology for health comparison across sampling groups

Overall, the project demonstrates how biologically grounded thresholds, combined with semantic logic modeling and computational tools, can produce a rigorous yet practical health evaluation system. The model bridges biological expertise and data-driven assessment, contributing to improved monitoring efficiency and evidence-based management in aquaculture and fish stock enhancement programs.

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