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**Food for Thought**

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# Risk understanding and risk acknowledgement: a new approach to environmental risk assessment in marine aquaculture

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A better understanding of the potential cumulative impacts of large-scale fish farming, could help marine aquaculture to become more environmentally sustainable. Risk assessment plays an important role in this process by elucidating the main challenges and associated risk factors. An appropriate aquaculture risk assessment should contribute to mutual risk understanding and risk acknowledgement among stakeholders, and thus common perspectives on measures and governance. In this paper, we describe an approach to risk assessment in marine aquaculture that aims to promote fruitful discussions about risk and risk-influencing factors across stakeholders with different value perceptions. We elaborate on the concept of risk and risk terminology and conclude that new aquaculture risk assessment methodology should be guided by risk science. The suggested methodology is based on the latest thinking in risk science and has been tested in a thorough study of environmental risk related to Norwegian aquaculture. The study shows that the new methodical approach has an immanent pedagogical potential and contributes to strengthening risk understanding and risk acknowledgement among stakeholders. In conclusion, the suggested risk assessment methodology has proved a valuable tool for marine scientists in analyzing, evaluating, and communicating environmental risk.

**Keywords:** environmental risk management, marine aquaculture, risk assessment methodology, risk communication, risk-informed decisions, risk science, risk understanding.

## Introduction

This paper describes a new approach to risk assessment in marine aquaculture. We argue that an approach that contributes to mutual risk understanding and promotes fruitful discussion about risk and risk-influencing factors across stakeholders with different value perceptions, is key to successful governance. Risk is defined in line with the latest thinking in risk science as *"the consequences of the activity with associated uncertainties"* (SRA, 2018a). The risk concept, thus introduces "consequences" and "uncertainties" as two key components that are connected. Contemplating the theoretical basis for assessing and communicating specific consequences and associated uncertainties in aquaculture is considered a core element in this paper. Moreover, an example on assessing environmental risk in Norwegian aquaculture is included to demonstrate feasibility, practical application, and the benefits of the suggested methodical approach.

### Norwegian aquaculture

The marine environment along the Norwegian coastline is affected by several commercial activities such as shipping, tourism, fisheries, energy production, and aquaculture. Even though these commercial activities to varying extent pose threats to vulnerable components of the marine ecosystems, they also pose value creation in terms of food, energy, jobs, and community income. Depending on commercial interests, value perceptions, political standpoint, and risk understanding, stakeholders tend to disagree with respect to strategic actions required to secure sustainable development of such industries (e.g. Bailey and Eggereide, 2020). The Norwegian aquaculture industry produce fish with an export value of more than 7.5 billion Euro annually, equivalent to 10% of the total Norwegian export (Statistics Norway, 2020). The core aquaculture production employs nearly 9000 people. When including services, goods, and equipment supplies to the aquaculture value chain, the industry employs about 30 000 man-years (Johansen *et al.*, 2020). Hence, fish farming in Norway, dominated by Atlantic salmon (*Salmo salar*), is a large and important industry, especially for many coastal communities where it contributes with associated business activities, jobs, and taxable income. On the other hand, with 400–500 million farmed fish located in open cages along the coast there is little doubt that this industrial activity affects the marine environment both locally and regionally (Taranger *et al.*, 2015; ICES, 2020).

Many Norwegians are to some extent affected by the fish farming industry, e.g. people directly or indirectly involved in farming (owners, employees, vendors, and so on), local and national politicians, the public administration, various advocating non-governmental organizations, coastal fishermen, salmon river owners, outdoor enthusiasts, anglers, and the vast number of regular Norwegian families using the fjords for recreational activities. In the public debate, some of these stakeholders tend to end up in polarized non-productive discussions where everyone owns their own version of the realities related to aquaculture environmental risks.

The Institute of Marine Research (IMR) has on behalf of The Ministry of Trade, Industry and Fisheries, conducted an annual risk assessment of Norwegian aquaculture since 2011,

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"Risk report Norwegian fish farming" (Taranger *et al.*, 2015). The risk assessment compiles knowledge of environmental impact-factors and contributes to a detailed picture of environmental effects of farming. The annual risk reports up to 2018, were comprehensive and rich in detail but the risk results were somewhat unclear and difficult to interpret, particularly for non-professionals. It was decided to change the methodological framework and in 2018 IMR assembled a project team to deliver a revised approach to be applied in the 2019 annual risk assessment (Grefsrud *et al.*, 2019).

### The need for a new approach to aquaculture risk assessment

The frameworks and guidelines for environmental risk assessment of aquaculture were established more than 10 years ago by an international Group of Experts on Scientific Aspects of Marine Environmental Protection (GESAMP, 2008) and FAO (Food and Agriculture Organization of the United Nations; Bondad-Reantaso *et al.*, 2008). They have since provided guidance and protocol to policy makers and other stakeholders on how to conduct aquaculture risk assessment. Based on the methodology suggested in GESAMP, (Taranger *et al.*, 2015) pioneered the development of aquaculture risk assessment in Norway. Moreover, GESAMP and FAO have inspired new developments of risk assessment frameworks such as; Framework for Aquaculture Risk Management (FARM) ("https://www.dfo-mpo.gc.ca/aquaculture/consultations/farm-cgra/farm/-cgra-eng.html,'' 2019) and guidelines for Assessing the Biological Risk of Aquatic Invasive Species in Canada (Mandrak *et al.*, 2012). There are, however, important differences in the way GESAMP and FAO define, describe, and measure risk compared to the developments in risk science. The latest thinking in risk science place knowledge characterization and subjective probabilities at the core of risk assessment. Both GESAMP and FAO however, emphasizes the importance of "…conducting risk assessments in the most objective way possible" and "…to reduce uncertainty to the extent possible" where uncertainties means deviations from a true and correct value (Arthur, 2008). The idea of objective probabilities (and thus, objective and true risk values) was originally developed for isolated environments such as casinos and laboratories and appears less useful in real life situations (de Finetti, 1974). The GESAMP and FAO frameworks seems to be anchored in the science of statistics rather than the science of risk. Statistics is the science about collecting, analyzing, presenting, and interpreting data. There are obviously overlaps, and risk science builds upon several fields and sciences like mathematics, statistics, uncertainty analysis, operations research, and management. There is, however, only risk science that provides guidance on concepts, principles, methods, and models for how to understand, assess, characterize, communicate, and manage risk (Hansson, 2013; Aven, 2020).

Inspired by *"Perspectives on the nexus between good risk communication and high scientific risk analysis quality"* by (Aven, 2018), it was decided that the new IMR risk assessment approach should lean on the latest thinking in risk science. The overall objective is to combine risk assessment principles and methodology that enhance risk understanding among stakeholders and promote constructive discussions on environmental risk related to aquaculture. Common risk terminology, mutual understanding of the risk concept, and illustrative methodology should make the interpretation of the risk results intuitive, unambiguous, and readily available to all stakeholders. Considering the interdisciplinary nature of the task, the team assembled by IMR consisted of senior researchers within both the risk science and disciplines relevant to aquaculture and the marine environment, whereof several with extensive practical experience on the GESAMP aquaculture risk assessment framework.

The first section of this paper "Attributes of a high-quality scientific aquaculture risk assessment" elaborates on the concept of risk, risk terminology, and the meaning of quality in aquaculture risk assessments. The following section describes the details of the suggested methodology for aquaculture risk assessment that aims to deliver on the high-quality attributes. The supplementary material includes a practical example on assessing environmental risks related to the use of wild caught wrasse for delousing in aquaculture. In the final two sections we offer a discussion and some conclusions on strengths, weaknesses, and potential improvements on the suggested methodology.

## Attributes of a high-quality scientific aquaculture risk assessment

What does a high-quality scientific environmental risk assessment in aquaculture really mean? In general, high-quality is associated with some level of excellence, usefulness (judged by the users), and the absence of errors (Bergman and Klefsjö, 2010). According to Society for Risk Analysis (SRA, 2018b), a high-quality risk assessment has credibility among stakeholders and meets some basic scientific requirements, i.e. it is relevant and useful; reliable and valid; and it is solid (complying with all rules and assumptions; the basis for all choices, judgments, and so on, are clear; principles and methods are subjected to order and system; and so on). Understanding the meaning of "probability" and "uncertainty" are key to understanding risk, reliability, and validity. Thus, this section seeks to provide clarity to the terms' "probability" and "uncertainty" in a risk assessment context. Moreover, we elaborate on what it takes for an aquaculture risk assessment to be considered useful, valid, and reliable. Table 1 provides a summary of these quality attributes on aquaculture risk assessment in terms of definitions and measurements.

### Providing clarity to the meaning of probability and uncertainty in risk assessments

Interpreting the concept of probability has engaged scientists worldwide ever since Pascal and Fermat developed the rules for probability calculus in 1654 (Bernstein, 1996). Whilst a brief summary of the topic is considered sufficient for the scope of this paper, the interested reader is referred to the many contributors that addressed the concept of probability in risk analysis 20–30 years ago, e.g. (Apostolakis, 1988, 1990; Kaplan, 1988; Östberg, 1988; Watson, 1994; Aven and Pörn, 1998).

#### Frequentist probabilities

Jacob Bernoulli (1654–1705) and his contemporaries in the late 17th century formulated the law of large numbers as part of developing formal methodology for the quantitative analysis of games of chance. In general, the theorem means that in the long run, the average of a long series of observations may be taken as the best estimate of the true value of a vari-

**Table 1.** Environmental risk assessment: definition and measurement of usefulness (this paper), validity, and reliability (e.g. Aven and Heide (2009), Aven and Zio (2018)).

| Attribute | Usefulness | Validity | Reliability |
|---|---|---|---|
| Definition | The risk assessment is structured and displayed in such a way that decision makers in the public administration and other interested parties can fully understand and acknowledge risk. | The degree to which the risk assessment measures/describes what we are attempting to measure/describe. | The extent to which the risk assessment yields the same results when (different expert teams) repeating the analysis. |
| Measurement | The extent to which stakeholders are provided with; understanding of risk contributing factors; insight on background knowledge; and structure to discussions on risk. | The extent to which stakeholders are provided with characterizations of background knowledge securing awareness on whether the risk results carry weight. | Differences (among different expert teams) in the background knowledge, and in the transition from knowledge to probability. |

able. Hence, what is unpredictable based on a few, or a single observation becomes predictable and uniform when the number of observations grows larger. When adopting a frequentist probability interpretation in risk analysis we would assume that a true probability $p = P(A)$ exists for the occurrence of event $A$, defined as the fraction of times event $A$ occurs if the situation was hypothetically repeated an infinite number of times. Since the assumed true frequentist probabilities are mind-constructed quantities founded on the law of large numbers, we must assume that the situations repeated are independent of each other. In the risk assessment, we estimate a probability $p*$ of the true (objective) probability $p$ and are, thus challenged with describing uncertainties raised by the analysis in terms of deviations between our estimate $p*$ and the assumed true value $p$. This uncertainty can be inherent in e.g. the established modelling structure, faulty or imperfect information, or statistical variation. Frequency probabilities anchored in the law of large numbers has been embraced by industries that have access to large populations of relevant data, e.g. the gambling, pharmaceutical, and insurance industries.

### Subjective probabilities

Increased application of probability calculus within social sciences and economy during the 19th century gave birth to alternatives to the frequency interpretation of probability. The subjective theory was conceived simultaneously but independently by the British mathematician and philosopher Frank Ramsey (1903–1930) and the Italian mathematician Bruno de Finetti (1906–1985). The theory states that probabilities are subjective assessments of degrees of belief (expressions of certainty/uncertainty), and hence, no underlying true values exist (Ramsey, 1931). De Finetti, on the first page of his work "The Theory of Probability" (de Finetti, 1974), states that "probability does not exist," meaning that probabilities do not exist in an objective sense. De Finetti argues that given a number of individuals with different *a priori* beliefs, the posterior belief will converge on the same value if the group is presented with the same evidence or information. The subjectivistic theory of probability is considered by many risk analysts as the "true Bayesian approach" to risk assessment. This approach focuses on observable quantities and uses probabilities to express the uncertainties related to whether a specific future event or scenario will occur or not. The probabilities are conditioned on the experts' state of knowledge at the time of the assignment, i.e. any relevant information including observations and hard data. Thus, the probability $p$ of some event $A$ is conditioned on the knowledge $K$, and we write $P(A|K)$. Adopting subjective probabilities in risk assessment, we do not present the results as estimates of underlying true (objective) values, but rather as uncertainties (degree of belief) related to the outcome of future events. According to Aven and Reniers (2013), Lindley (2013), and SRA (2018a) an expert assigning a probability about the occurrence of event $A$ being e.g. equal to 0.1 considers this probability to be equivalent to the uncertainty/degree of belief in some standard event, for example drawing at random a particular ball from an urn that contains 10 balls. Transferring knowledge $K$ to numerical probabilities $P$ with associated combination of events and probability calculus may in some cases be complex, resource-intensive, and perhaps too fine-grained. Often, we simply want to convey experts' comparison of the probability of two events without using numerical quantities. In qualitative probabilistic reasoning, we assert that some event is more probable than another without specifying the numerical probabilities of the events in question, but rather use high/low, higher/lower than. Such an approach may offer a pragmatic, intuitive, and practical counterpoint to quantitative probabilities and are scientifically explored and utilized in many professions, see e.g. Kong *et al.* (1986) and Shaw and Dear (1990) on applications in medicine, and Delgrande and Renne (2015) in artificial Intelligence.

## On usefulness, validity, and reliability in aquaculture risk assessments

The adjective "useful" is defined by the Oxford English Dictionary (2021) as "able to be used for a practical purpose." Merriam-Webster Dictionary (2021) defines the noun "usefulness" as "the quality of having utility and especially practical worth or applicability." Whether an aquaculture environmental risk assessment can be considered useful should be seen in relation to the specific context of how aquaculture is governed. That is, how the results will be utilized by stakeholders, and whether the risk assessment is structured and displayed in such a way that decision makers and other interested parties are able to fully understand and acknowledge risk. Considering the complex political dynamics of aquaculture governance, it is essential that risk understanding is achieved among all stakeholders e.g. advocating non-governmental organizations, industry representatives, politicians, and public administration, as well as the public. The aquaculture risk assessment should be considered a sound starting point for discussions on risk (rather than a revelation of the truth) and incrementally updated and changed based on valid arguments by stakeholders. In this paper, it is argued that an aquaculture risk assessment should be considered useful when forming a sound starting point for discussions on risk and contributes to mutual risk acknowledgement across stakeholders with diametrically different value perspectives. Hence, the risk assessment should provide stakeholders with insight on overall causal structures and facts related to risk influencing factors. Securing such insight provides structure to the discussions on risk and may lead to a shift in focus from the end results where stakeholders may or may not like and/or accept risk, to an understanding of risk contributing factors, causal mechanisms, and the knowledge that formed the basis for the assessment. Thus, giving rise to more fruitful, fact-based, and structured discussions on risk and risk mitigating strategies.

### Validity and reliability

Aven and Heide (2009) discusses risk assessment quality in relation to the terms' "validity" and "reliability" defined as:

- *Validity:* the degree to which the risk assessment measures/describes what one is attempting to measure/describe.
- *Reliability*: is concerned with consistency and the extent to which the risk assessment yields the same results when repeating the analysis.

Validity is generally associated with solidity, completeness, and precision. Thus, the validation of a risk assessment gives rise to some level of credibility and trustworthiness (Goerlandt *et al.*, 2017). Stakeholders' trust in an aquaculture risk assessment expected to be holistic would obviously be very low if well-known environmental threats are not included in the analysis. Moreover, if the assessment applies frequentist probabilities, and thus aims to estimate an assumed true underlying risk, the quality judgment would have to focus on to what extent the risk estimate is accurate. Alternatively, we may adopt a true Bayesian approach to the risk assessment, where experts' degree of beliefs is expressed by subjective probabilities $P$ based on all available knowledge $K$ such as e.g. monitoring, modelling, experiments, observations, expert argumentation, and statistical analyses. In this context, judging risk assessment validity with focus on the precision of the probability $P$ gives no meaning since $P$ is merely a tool for subjective or inter-subjective expression of uncertainties related to the occurrence of future events, and there is no true objective reference point to measure $P$ against (Aven and Zio, 2018). Thus, the validity judgement should focus on the description and evaluation of the background knowledge $K$ as a part of the risk assessment. Aven and Zio (2018) conclude that to meet basic quality requirements risk can seldom be described adequately by probabilities alone and advocates an approach that aims at knowledge characterization. Characterization of the background knowledge provides the stakeholders with awareness on to what extent the results from the risk assessment carry weight. Strong knowledge means the risk results carry much weight, whilst weak knowledge may lead stakeholders to question whether the risk assessment is valid. Berner and Flage (2016) argue that transition processes from $K$ to $P$ may hold severe limitations and underline the importance of systematically reviewing uncertain assumptions. Weak knowledge indicated by e.g. hypotheses, uncertain assumptions, or disagreements among experts may conceal potential threats, vulnerabilities, and consequences that could materialize in the future as total surprises. Surprises where the consequences reach catastrophic proportions are often referred to as "black swan" events as described by Taleb (2007). Analyses of the potential for surprises, relative to current knowledge are suggested carried out as an explicit part of the knowledge characterization for an aquaculture risk assessment to be complete.

Aven and Heide (2009) define reliability in the context of risk assessment as to what extent the assessment yields the same results when repeated, be it reruns of the same approach or different analysis teams applying different methods. Even if aquaculture risk assessments with different assessors satisfies the above validity criteria, there may be expect some differences in both the background knowledge, and in the transition from $K$ to $P$. The differences should, however, be relatively small if the different teams of assessors all include professional expertise, does not express any stand on matters, and lean on updated scientific knowledge related to aquaculture. Adopting the uncertainty and knowledge characterization perspective on aquaculture risk assessment, the focus is on presenting a sound basis for productive discussions about risk, and thus reach common risk understanding among stakeholders. In this perspective, moderate differences between two teams of experts in the way $P$ and $K$ is described may contribute to constructive scrutiny of the background knowledge and discussions on the transition of specific knowledge to measures of environmental risk posed by aquaculture. Strong disagreements among experts may however indicate weak knowledge and the potential for surprises should be examined thoroughly.

## Suggested approach to aquaculture risk assessment methodology

This section describes the suggested approach to aquaculture risk assessment, starting out by explaining the necessary fundamentals that forms the basis for how the risk results are to be understood, and thus communicated. The supplementary gives a detailed example of application (including notes to the reader) related to an environmental risk assessment on the use of wild caught wrasse as cleaner fish in open cage salmon farming. Glover *et al.* (2020) also provide an example of application of this methodology on "Further introgression of domesticated escapees in the thirteen production zones," based on Grefsrud *et al.* (2019).

In line with SRA (2018a), risk is defined as *"the consequences of the activity with associated uncertainties"* i.e. the pair *(C, U)* where C are the consequences of the activity and *U* express that these consequence are unknown. The consequences can be split into risk sources *(RS)*, events *(A)*, and consequences *(C)*. Hence, as given by e.g. Aven (2014), risk can be defined by *(RS, A, C,* and *U)* with corresponding risk description *(RS´, A´, C´, Q,* and *K)* where *RS'*, *A'*, and C' are specific risk sources, events, and consequences of aquaculture activities, respectively. *Q* is a measure of uncertainty associated with whether risk sources (*RS'*), events (*A'*), and consequences (*C') occurs*. *K* is the background knowledge that supports *RS'*, *A'*, *C'* , and *Q*. The uncertainty *Q* is measured by *(P, SoK,* and *K)*, where *P* is subjective/knowledge-based probabilities, *SoK* is judgements of the strength of knowledge supporting the probabilities, and *K* is the knowledge that *P* and *SoK* are based on. At this point, it is suggested to express experts' uncertainties related to future outcomes in terms of qualitative probabilities assessed as high, moderate, or low, and strength of knowledge *SoK* as strong, moderate, or weak. For now, we simply want to convey experts' comparison of the likelihood of influencing factors impact, such as Glover *et al.* (2020) that applied

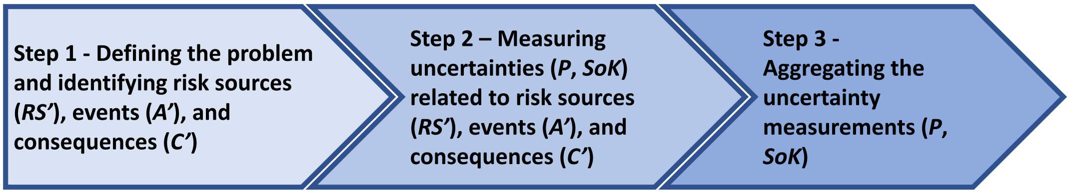

**Figure 1.** Diagram showing the risk assessment process.

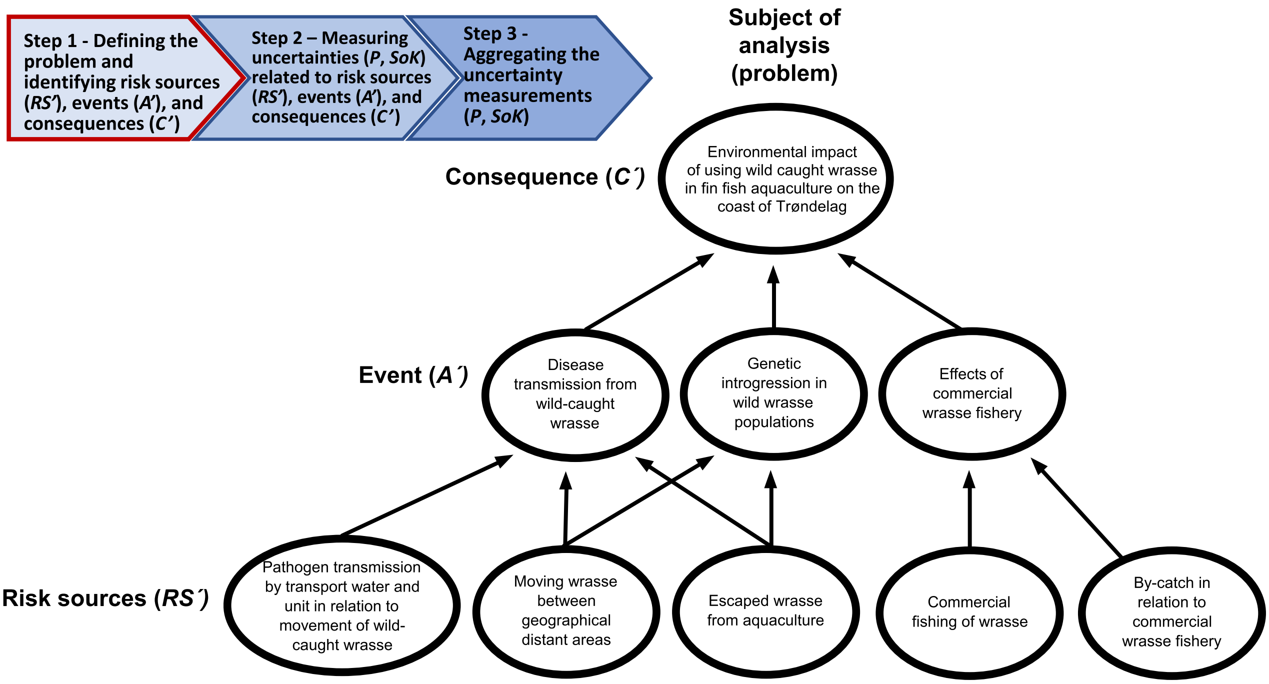

**Figure 2.** Step 1 of the risk assessment process: structuring of specific consequences, events, and risk sources associated with the environmental effects of using wild-caught wrasse for delousing of salmonids in fish farming on the coast of Trøndelag, Norway (modified from Grefsrud *et al.*, 2021).

qualitative probabilities to expresses their uncertainties related to further introgression of domesticated escapees. Another example is Mimeault *et al.* (2017) that applied qualitative probabilities in risk assessments on nine pathogens on Fraser River Sockeye salmon. The qualitative probabilities should be interpretated as subjective expressions of uncertainty/degrees of belief related to the outcome of future events. Applying qualitative rather than numerical probabilities make no difference however, with respect to the importance of describing *K* thoroughly, i.e. the reasoning behind the probability assessment that contributes to risk understanding and risk acknowledgement. Moreover, the risk results resting on qualitative probabilities should be communicated the same way as numeric probabilities, i.e. subjective knowledge-based expressions of uncertainties related to future outcomes.

Risk-contributing factors are suggested visualized in a graphical cause-and-effect structure to enhance risk understanding and help structuring discussions on risk among stakeholders. Striking the right balance between required details to promote understanding on the one side, and too many details enhancing complexity and incomprehensibility on the other, is considered a key element in this process. The graphical structures visualize causal relationships (risk sources, events, and consequences) and uncertainties in terms of subjective probabilities and strength of knowledge. Following the rules of Bayesian belief networks (BBN) is suggested in designing these graphical structures' (Jensen and Nielsen, 2007), where BBN consists of: a set of nodes (i.e. risk sources, events, and consequences) and a set of directed edges between nodes; each node has a set of mutually exclusive states; and the nodes together with the directed edges form an acyclic directed graph. Thus, loops or feedback cycles are not allowed. The nodes describe risk sources, events, and consequences at different hierarchical levels. To promote quick and intuitive risk-understanding a simple graphical structure has been chosen that is characterized by; a top-down approach to structural design; a top node illustrating the problem; maximum four levels of underlying nodes; and a bottoms-up approach to risk evaluation. The risk assessment process is, thus made up of three main steps (Figure 1), i.e. (1) defining the top node and designing a graphical structure of underlying nodes in terms of risk sources *(RS´)*, events *(A´)*, and consequences *(C´)*; (2) measuring the uncertainties related to risk sources, events, and consequences in terms of subjective probabilities *(P)* and strength of knowledge *(SoK)*; and (3) aggregating the uncertainty measurements of each node upwards until reaching the top node.

## Step 1–defining the problem and identifying risk sources, events, and consequences

First, the top node is defined constituting the subject of analysis with focus on *what* the problem is and *where* it may occur, e.g. “Environmental impacts of using wild caught wrasse in fin fish aquaculture on the coast of Trøndelag.” Then the associated underlying nodes are identified in terms of risk sources and events that form a graphical cause-and-effect structure (Figure 2).

Putting the final graphical structure together is seldom strait forward and may be time consuming. A natural starting point for the expert group (in this case professional experts on disease, wrasse ecology, and wrasse fishery) would be a discussion on all thinkable contributing factors, i.e. risk sources, events, and consequences, based on updated knowledge such as peer-reviewed publications, statistics, and available reports. Members of the expert group often start out by including quite a lot of details that they find important. This may result in an intricate and complex first draft of the graphical structure. The experts should, however, keep in mind the need for striking the right balance between details and main concerns to secure stakeholder risk understanding. Undoubtedly time consuming, but this part of the process will ensure thorough discussions that enlightens most (hopefully all) aspects concerning the subject of analysis. Through these discussions it will be apparent that the strength of knowledge on the different nodes varies, and that more or less well-founded assumptions are (frequently) made. This knowledgebase should be thoroughly documented, and thus contribute to stakeholder insight on the background for the chosen cause-and-effect structure. With the graphical structure and associated knowledge description, arguments, and assumptions in place, the next step will be assessing the uncertainties related to risk sources, events, and consequences.

## Step 2–assessing uncertainties related to risk sources, events, and consequences

Uncertainties related to a specific event is measured by the triplet *(P, SoK,* and *K)*. Starting at the lower-level nodes, a probability *P* is assigned to each specific risk source *RS´*. The probability *P* express the experts’ degree of believes in terms of high, moderate, or low probability related to *RS´* occurrence. Assigning a reference point to each node in terms of *a desired state* may help in the probability assessment process. *The desired state* is defined as: *“a state where the probability for the occurrence of the RS´, A´ or C´ in question is considered low or negligible by the expert team, and/or in line with accepted threshold values assessed by governmental bodies.”* Assessing the *current state* of each node per time of the risk assessment with subsequent analysis of deviations from the *desired state* provides insight that supports the process of assessing probabilities related to *RS´*, *A´*, and *C´*. As an example, *the current state* of the risk source “moving wrasse between geographical distant areas” is considered to be far from *the desired state* and the probability for the specific *RS´* occurrence on this location is, thus judged to be high, ref. Figure 3. The magnitude of *P* is indicated and visualized by colouring the node red, yellow, or green for high, moderate, or low probability, respectively.

The magnitude of *P* for a specific node is based on some level of knowledge *K* that should be documented thoroughly.

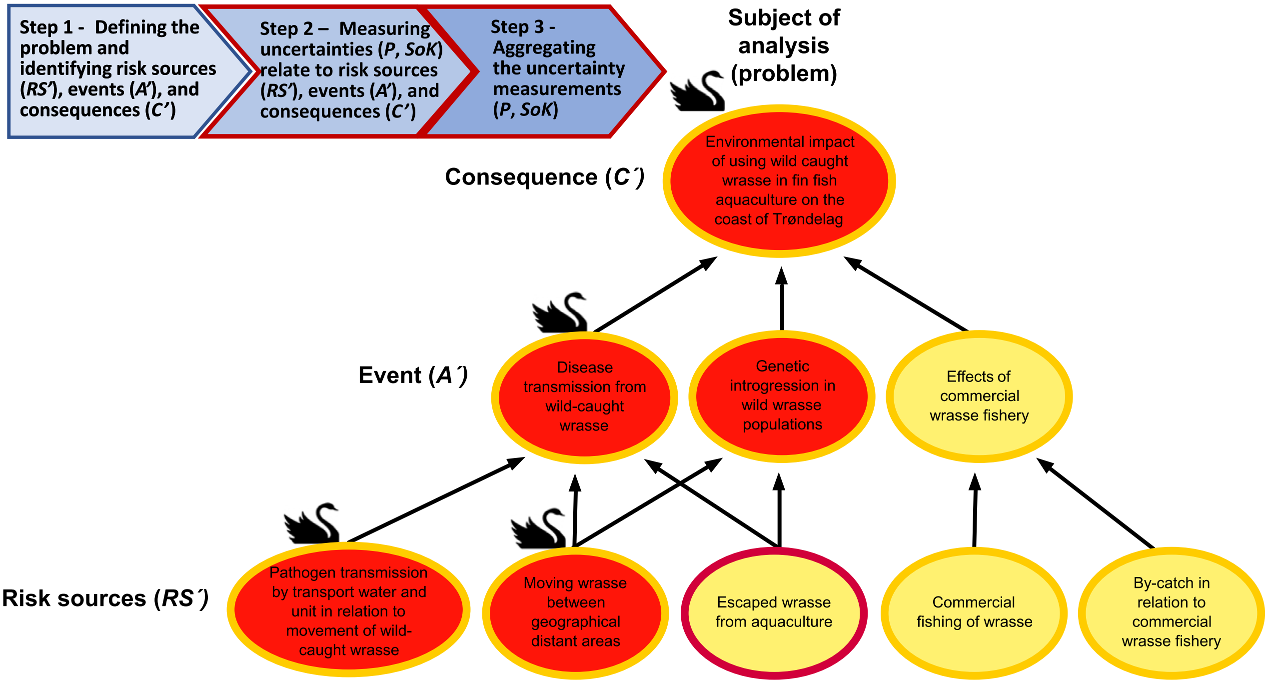

**Figure 3:** Steps 2 and 3 of the risk assessment process: measuring and aggregating the uncertainty of each node until reaching the top node of the risk diagram (modified from Grefsrud *et al.*, 2021). The colour of a node displays the probability *P* (experts’ degree of belief) of the events occurrence (in terms of high (red), moderate (yellow), or low (green) probability). The strength of knowledge (*SoK*) is displayed as a circle around the node (i.e. strong (green), moderate (yellow), or weak (red) knowledge). The black swans symbol visualizes the potential for surprises.

The knowledge *K* may be anchored in hard data, statistical analyses, testing, modelling, simulations, and research reports. If the knowledge (upon which *P* is based) is considered solid with large degree of agreement among experts in the field, we may conclude that the strength of knowledge, *SoK* is strong. As an example (ref. Figure 3), the knowledge that forms the basis for assigning a moderate probability for the occurrence of the *RS´ "escaped wrasse from aquaculture"* is judged to be weak. The strength of knowledge evaluation is based on the argument; *"since there is no formal counting of the proportion of wrasse that escape from net pens"* (quotation from supplementary material). The *SoK* assessment is visualized by colouring the circle around the node, green, orange, or red for strong, moderate, or weak strength of knowledge, respectively. The effect of assessing the strength of knowledge becomes particularly evident when analyzing the potential for surprises—so called "black swan events." The metaphor was first presented by Taleb (2007) and further scrutinized, discussed, and developed in a risk-assessment context by risk science professionals such as, e.g. (Gross, 2010; Paté-Cornell, 2012; Lindley, 2013; Aven, 2014). Aven (2014) describes surprises (black swan events) to appear unexpected in the light of current knowledge/believes and to carry severe consequences. We argue that the experts involved in the aquaculture risk assessment should dedicate time to analyse the potential for such surprises, especially where combinations of weak knowledge and poorly founded assumptions and hypotheses are present, and thus may contribute to concealing risk. A total of two out of three risk sources affecting the event *"Disease transmission from wild caught wrasse"* in Figure 3 are marked with a black swan indicating surprises. The interested reader is referred to the supplementary material for detailed arguments on why the two risk sources *"Pathogen transmission by transport water…"* and *"Moving wrasse between geographical distant areas,"* both characterized by moderate knowledge strength, are judged to hold potential for surprises.

### Step 3–aggregating uncertainty measurements

In the third step of the risk assessment process, the hierarchy of uncertainty assessments (*P* and *SoK*) are aggregated to eventually reach a conclusion at the top node. This process starts at the bottom-level by combining the uncertainty–evaluations of the risk sources influencing the same overlying event, i.e. the probability of *A'* occurrence is conditional on some specific underlying risk sources *RS'* and the background knowledge *K*. Consider an example where all bottom-level risk sources with arrows aimed at the same specific overlying event are evaluated to be far from their desired states with, thus high probability for occurrence (colour code red). Then the overlying event must also be far from the desired state (given that all relevant risk sources are included) and should, thus be assigned a high probability for occurrence. In some cases, risk sources are judged to carry different weigh that must be taken into considerations when aggregating the risk evaluations.

Applying the suggested methodology, it should be kept in mind that the characterization of the background knowledge *K* is considered a key component of the risk assessment. The figures with hierarchical structures of risk sources, events, and consequences with associated colour codes and symbols are meant to support the knowledge descriptions in terms of visualizing the risk components; *RS'* (specific risk sources), *A'* (specific events), C' (specific consequences); P (probability reflecting the experts' degree of belief in specific factors impact); and SoK (the strength of background knowledge up on which C' and P, are assessed).

## Discussion

This paper presents the latest thinking in risk science with application to aquaculture environmental risk assessment. The concept of risk and associated risk terminology are elaborated aiming to build a sound starting point for marine scientists to reflect upon how the results from their planned risk assessment eventually should be interpreted and understood. Marine scientists (trained in the science of statistics) often adopt a frequentist interpretation of probabilities in the environmental risk assessments aiming to estimate true/objective risk levels, even though; hard data are deficient; explaining uncertainties (i.e. deviations from true risk levels) are challenging; and some stakeholders questioning validity is inevitable. Environmental hazards related to aquaculture are for the most part characterized by; a vast number of influencing factors; frequent lack of hard data; and the need for multidisciplinary expert input. Insisting on a frequentist approach can, as emphasized in the present paper, lead to weak validity (low precision) and sometimes even paralysis of action unable to deliver any risk insight at all (refraining from conducting a risk analysis due to lack of hard data). These shortcomings can be dealt with in an approach to aquaculture risk assessment that provides knowledge-characterization on factors affecting what lays ahead and motivates sound discussions on risk (Aven and Zio, 2018), rather than revelations of the truth promoting less constructive discussions on uncertainties in risk estimates. Moreover, the approach should be an enabler for risk analyses also when hard data are scarce and current knowledge is generally weak. Hence, this paper recommends the application of subjective probabilities for environmental risk assessments in aquaculture that reflects experts' degree of belief when assessing uncertainties related to future outcomes (de Finetti, 1974; Aven and Pörn, 1998). These probabilities are conditional on some level of knowledge that may include research reports, scientific papers, testing, monitoring, observations, modelling, statistical analysis, and so on. It is argued that inclusion of thorough descriptions and evaluations of this background knowledge are key to stakeholders' perceptions of the risk assessment as useful, valid, and reliable. Risk results based on strong background knowledge carry a lot of weight whilst weak knowledge may conceal potential threats and vulnerabilities that can occur as total surprises carrying severe environmental impact.

For now, risk is expressed qualitatively rather than quantitatively in the suggested approach to aquaculture risk assessment. Presenting the risk results in terms of numbers (rather than qualitatively as high, moderate, or low) may, however, strengthen the overall usefulness by; enabling sensitivity studies of risk-influencing factors; study risk-reducing effects of alternative measures; and make comparison with numerical threshold-values. Decisions to further develop the methodology to include numerical risk figures should, however, be based on whether the required increase in resources related to converting knowledge to numerical figures and risk modelling are justified by the added value for stakeholders.

The probability and consequence matrix was considered a natural starting point for discussion when the task force consisting of marine- and risk scientists evaluated alternative methodology for aquaculture risk assessment. Being easy to use and understand by non-professionals the risk matrix is by far one of the most common ways of conveying risk results today, independent of industry or profession. On the other hand, the risk matrix has also received serious criticism from risk scientists, such as Cox (2008). Considering the objective of creating risk understanding by presenting unambiguous and readily available risk results, it seems clear that stakeholders would benefit from visualization of overall cause-and-effect structures combined with insight on risk influencing factors. The immanent pedagogical potential and intuitive understanding that comes from visualization of causal structures are however, beyond the range of a 2D risk matrix. Instead, the choice fell on a simple hierarchical structure following the rules of Bayesian Networks (BN) design (Jensen and Nielsen, 2007).

The suggested approach to aquaculture risk assessment presented in this paper has been applied and tested in the 2019, 2020, and the 2021 version of "Risk Report Norwegian Aquaculture" (Grefsrud *et al.*, 2021). The feedback from stakeholders has been predominantly positive. Particularly the readily available risk results in terms of simple visualized cause-and-effect structures and associated qualitative probability- and strength of knowledge assessments got warm receptions from stakeholders. Positive feedback from stakeholders has also been given on visualization of overall causal structures and condensed descriptions of the background knowledge *K*. The causal structures and descriptions of background knowledge are judged by stakeholders to provide both important insight and pedagogical structures that promote more fruitful and less value laden discussions on risk. Participants in the discussions are on some level bound to take a stand on; whether risk sources are relevant, missing, or misplaced; whether they accept the professional experts' knowledge characterization and evaluation; and whether they find the arguments supporting the experts' degree of belief in specific outcomes convincing. Also, pointed out by several stakeholders, however, is the fact that the quality of the risk assessment results are inseparably attached to, and thus sensitive to the expert group's composition and collective competence. Moreover, at this point the risk assessment process culminates with an annually published report presented to all interested parties. Stakeholders within the public administration points out an improvement potential in terms of a more dynamic risk assessment process that incorporates early involvement of stakeholders, and continuous updating of risk results (as new knowledge emerges). The authors acknowledge this as a valid point with respect to the overall risk assessment process that is in line with current thinking in risk science. Incorporating early involvement requires few changes to the suggested methodology, but rather to the project plan where stakeholders could be involved already at the stage when a draft structure of all influencing risk factors are in place (step one in Figure 1). A continuous and dynamic updating of the risk results as soon as new knowledge emerges may require both organizational focus and digital resources but few changes to the methodology as such.

## Conclusion

In line with current thinking about risk (SRA, 2018b), we recommend a true Bayesian approach to aquaculture risk assessment where subjective probabilities express experts' degree of belief. The knowledge *K* that forms the basis for assessing consequences and associated uncertainties should be thoroughly characterized. Weak knowledge where important data and information are missing or unreliable, along with a poorly understood phenomena, disagreements among professional experts, and/or assumptions representing strong simplifications may indicate potential surprises that should be further scrutinized.

There are obviously many alternative ways of conducting risk assessments that would form an adequate basis for risk communication, constructive discussions on risk, and eventually sustainable governance. The many approaches to high quality scientific aquaculture risk assessment contributing to risk understanding and risk acknowledgment comes with varying interpretations of the risk concept, and different methodologies conveying the risk picture in different manners, both qualitatively and quantitatively. Any approach to environmental risk assessment of aquaculture should, however, be expected to lean on contributions from risk science, hereunder considered useful in terms of promoting risk understanding and risk acknowledgement for all stakeholders.

As a final remark, we point out the importance of decision-makers and others using the results from a risk assessment understanding that incomplete information, insufficient knowledge, hypotheses, and assumptions are all part of, and largely characterize, an analysis such as this.

## Data availability statement

The data underlying this article are available in the article and in its online supplementary material.

## Supplementary material

The following Supplementary material is available at ICESJMS online, providing a detailed description of the example of application "Environmental impacts of using wild caught wrasse in fin fish aquaculture on the coast of Trøndelag in mid-Norway" (modified from Grefsrud *et al.*, 2021), used in this paper. This example demonstrates the feasibility and benefits of the suggested approach to aquaculture risk assessment, and it also includes notes to the reader.

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## Competing interest statement

The authors of this article have no potential competing interest to report.

## Author contributions

Andersen and Grefsrud devised the project and the main conceptual ideas. Andersen authored the risk fundamentals and the theoretical basis for the new methodology. Andersen, Grefsrud, Sandlund, and Svåsand wrote the manuscript and contributed to customization of the risk fundamentals for application in environmental risk assessment in general, and aquaculture in particular.

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