Implementing an uncertainty-based risk conceptualisation in the context of environmental risk assessment, with emphasis on the bias of uncertain assumptions

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Environmental risk assessments are routinely carried out in the Norwegian petroleum industry. As this industry is moving north, towards the Arctic and into areas with differing vulnerabilities and new risk sources compared to the now well-developed areas, previous operational experience and analytical practice may become less relevant. Reflecting the lack of knowledge (i.e., the uncertainty) that exists, and the strength of the available knowledge, then becomes critical. In the present paper, we review and discuss the industry guideline that for a long time has formed the methodological basis for these assessments, focusing on its foundation concerning risk and uncertainty. We conclude that there is a potential for improvement, and to contribute to improving the guideline, we describe how to implement – in the context of environmental risk assessment – a framework for conceptualising risk and its description that is consistent with the new uncertainty-based risk perspective recently adopted by the Petroleum Safety Authority Norway and in the Society for Risk Analysis glossary. The implementation includes a description and exemplification of a method for assessing the bias of uncertain risk assessment assumptions.

Keywords: environmental risk assessment; uncertainty; knowledge; assumption bias; Arctic

1. Introduction

Environmental risk assessments (ERAs) are routinely carried out in the Norwegian petroleum industry, as a basis for decision-making on risk acceptance and risk-reducing measures such as oil spill response systems and measures. The Norwegian petroleum regulations (PSAN 2010b, sec. 17) require operators to perform and use ERAs as a basis for managing environmental risk, including as a basis for establishing emergency preparedness to handle acute discharges. The ERAs are typically performed according to the well-established industry guideline ‘Method for environmental risk assessment’

(DNV 2007).

The Norwegian petroleum industry is currently moving north, towards the Arctic and into less developed areas with environmental components of potentially differing vulnerabilities, as well as new risk sources compared to the now well-developed areas on the Norwegian continental shelf. For example, cold climate factors, such as icing, polar lows, and icebergs, can be seen as risk sources specific to the Arctic setting. Previous operational experience and analytical practice could then be less relevant, and reflecting the lack of knowledge (i.e., the uncertainty) that exists and the strength of the available knowledge (e.g., the 'goodness' of models), then becomes critical.

A recognition of the need for new analytical practice in the Arctic, for example, prompted the development of a methodology for calculating environmental risk for the marginal ice zone (MIZ) (DNV GL & Akvaplan-niva 2014). The MIZ methodology is described as 'an approach within the current [ERA] method' (DNV GL & Akvaplan-niva 2014, 3). The ERA guideline described at the beginning of this section thus still constitutes the overall assessment approach to be used. The new MIZ methodology document addresses more detailed and technical issues related to oil drift modelling in the marginal oil zone, effect and damage keys (i.e., dose-response functions), and presents a review of datasets on environmental resources.

In the present paper, we first review and discuss the ERA guideline (DNV 2007), focusing on its foundation concerning risk and uncertainty. Based on the review, we conclude that it is based on a risk conceptualisation that is no longer fully in line with that now recommended by the Petroleum Safety Authority Norway (PSAN), which conceptualises risk as 'the consequences of the activities, with associated uncertainty' (PSAN 2015, sec. 15). We find that there is a potential for improvement regarding both the risk conceptualisation and the uncertainty treatment. In the second part of the paper, we aim to contribute to improving the guideline by describing how to implement – in the context of ERA – a framework for conceptualising risk and its description that is consistent with the new risk perspectives recently adopted by the PSAN and in the Society for Risk Analysis (SRA) glossary (SRA 2018). The implementation includes a description and exemplification of a method for assessing the bias of uncertain risk assessment assumptions.

The remainder of the paper is organised as follows: In Section 2, we review the new definition of risk adopted by the PSAN, and in Section 3, we review and discuss the ERA guideline. Then, in Section 3, we describe a framework for conceptualising risk and its description, adapted to the environmental risk assessment setting, as well as a method for assessing the bias of uncertain risk assessment assumptions. We then discuss the framework and suggestions in Section 4, before concluding in Section 5.

2. The new PSAN risk definition

The PSAN recently changed the definition of risk in the guidelines to the Framework Regulations (PSAN 2015, sec. 11). Until 2015, the definition of risk in these guidelines was (PSAN 2010a, sec. 11): ‘By risk is meant a combination of probability and consequence’. As of 2015, the PSAN defines risk as follows (PSAN 2015, sec. 11): ‘Risk means the consequences of the activities, with associated uncertainty.’

The Petroleum Safety Authority Norway (PSAN 2016) describes the new risk definition as a ‘clarification’ rather than as a change that implies new requirements. Three objectives of this clarification are stated (PSAN 2016, 6):

- ‘We want to facilitate a better understanding of risk management requirements and a better compliance between practice and regulatory intentions. […]

- We want to help increase the value of risk assessments in parts of current practice. For example, a discussion of the contents of the concept of risk may contribute to more efforts being used on management than on documentation.
- We want to support the good work that is done in the companies and contribute to the necessary further development regarding continuous improvement of risk management.'

The term uncertainty is explained by the PSAN (2016, 8) as: 'Uncertainty is about lack of information, lack of understanding or knowledge.' The PSAN (2016) emphasises that introducing this term to replace probability in the definition of risk is in line with international standards such as ISO 31000, and states that an aim of doing so is to move away from a 'mechanical' assessment of probabilities since these may conceal uncertainties. Regarding the term consequences, the PSAN (2015, para. 11) stresses that 'The term is not solely limited to the final consequences of the activities in the form of e.g. harm to or loss of human lives and health, environment and financial assets, but also includes conditions and incidents that can result to or lead to this type of consequences.' The term consequence is thus used in a wide sense by the PSAN, to include not only end/final consequences but also events/hazards and risk sources. For example, not only loss of environmental components (fish, birds, etc.) but also the occurrence of the release leading to such losses as well as factors/conditions related to the release, such as the magnitude, place and duration of the release, are considered consequences according to this definition.

The second risk definition in the first paragraph of this section is in line with the way the risk concept is defined in the recently published Society for Risk Analysis (SRA) glossary (SRA 2018). The first definition above is in line with one of the risk metrics included as an example of one way to describe risk in the SRA glossary. One of the hallmarks of the SRA glossary is that it distinguishes between overall qualitative definitions of concepts on the one hand, and measurements associated with these concepts on the other. For example, seven different qualitative definitions of risk (labelled a) through g)) are listed in the SRA glossary, including (SRA 2018, 3):

> ‘d) Risk is the consequences of the activity and associated uncertainties.’

The new PSAN definition is thus very close to definition d) above. Furthermore, the SRA glossary gives six examples of risk metrics/descriptions, including (SRA 2018, 3–4):

> 1. ‘The combination of probability and magnitude/severity of consequences.
> 2. [...]
> 3. The triplet (s_i,p_i,c_i), where s_i is the ith scenario, p_i is the probability of that scenario, and c_i is the consequence of the ith scenario, i=1,2,…,N.
> 4. The triplet (C’,Q,K), where C’ is some specified consequences, Q a measure of uncertainty associated with C’ (typically probability), and K the background knowledge that supports C’ and Q (which includes a judgment of the strength of this knowledge).
> 5. Expected consequences (damage, loss) [...]’

The previous PSAN definition is thus similar to definition 1 above. Definitions 5, 1, 3 and 4 can be said to have an increasing level of generality, in that order. This can be seen by noting that 5 defines risk as an expected value, i.e., as the product of consequences and associated probabilities; 1 defines risk as the combination of these components, i.e., not necessarily the product; 3 adds scenarios compared to 1; and 4 replaces probability with a general uncertainty measure.

Definition 4 above also adds the background knowledge, K, to the risk description. One approach to describing risk that is consistent with definition 4 is to let the uncertainty measure, Q, cover probabilities, P, as well as qualitative strength of knowledge judgements, SoK; i.e., to let Q = (P,SoK). Different schemes exist for qualitatively reflecting strength of knowledge judgements in risk assessments. One is the so-called NUSAP notational scheme (Funtowicz and Ravetz 1990). Another scheme, developed specifically for the risk assessment setting, is the set of criteria and associated classification rules for categorising the strength of knowledge, proposed by Flage and Aven (2009). A further example is the set of assessment factors described by the US Environmental Protection Agency (EPA) for evaluating the quality of scientific and technical information (EPA 2003).

3. Review and discussion of the environmental risk assessment guideline

In this section, we first briefly review the method for environmental risk assessment (ERA) described in the guideline (DNV 2007): its background and purpose, as well as its main types, and steps. We then narrow in on the concepts of risk and uncertainty, focusing on how the guideline defines and suggests how to describe and represent these concepts. First, however, we comment on the scope and related literature of the guideline.

The scope of the examined ERA guideline is the overall process of environmental risk assessment related to ‘large’ oil spills (DNV 2007). The literature contains numerous other overall frameworks, approaches, and methodologies, providing guidance on how to perform ERAs in petroleum exploration and production as well as in other areas of application. Examples include a framework for environmental risk assessment/management for climate change impact assessments (Jones 2001), frameworks related to risk assessment and management of nanoparticles (Morgan 2005; O’Brien and Cummins 2011), a framework and associated methods for updating uncertainty in an integrated environmental health risk assessment (Brand and Small 1995), and a framework for predictive environmental risk assessment of chemical mixtures (Backhaus and Faust 2012). Although rather dated, Power and McCarthy (1998) give an overview and comparison of 'representative' environmental risk assessment/management frameworks from different countries and agencies, including the US EPA, the US National Research Council, and the UK Department of the Environment. Moreover, the US EPA currently maintains a set of online resources related to environmental risk assessment; human health risk assessment and ecological risk assessments, in particular (EPA n.d.). There are also numerous literature sources addressing uncertainty – as well as related concepts, such as variability – in the context of environmental risk assessment. Examples include a framework for uncertainty in environmental modelling processes (Refsgaard et al. 2007), an analytical framework for integrating uncertainty and inter-individual variability in ERAs (Bogen and Spear 1987), a method for conservative uncertainty propagation in ERAs (Ferson and Long 1995), and methods for probability bounds analysis in ERAs (Tucker and Ferson 2003).

3.1. Environmental risk assessment method

The first version of the method for ERA described in the guideline was developed in the period 1994–2000, as a collaboration between various oil and gas operators and the then Norwegian Oil Industry Association (DNV 2007). The guideline has been revised several times since its first edition, most recently in 2007. The 2007 revision (DNV 2007) is the one considered in the present paper. The description in the remainder of this section is based on (paraphrased) or taken from the guideline (quotes are indicated).

The ERA guideline 'provides a common approach and forms a common framework for performing environmental risk assessments' (DNV 2007, 1). It 'involves the standardisation of several parameters, input data, and sub-assessments', with the intention that assessments should be comparable across different companies (DNV 2007, 1).

The guideline describes an ERA as ‘a systematic process by which information about a number of conditions is obtained and systematised to carry out a quantitative analysis’ (DNV 2007, 1). Several potential purposes of an ERA are mentioned, among these to evaluate compliance with risk acceptance criteria and to serve as a basis for selecting and dimensioning risk-reducing measures such as oil spill response (DNV 2007).

The guideline distinguishes three types of assessment with increasing level of detailing, namely:

- Reference-based assessment
- Exposure-based assessment
- Damage-based assessment

A reference-based assessment ‘provides a quick indication of the risk level based on a minimum of input data. This is the least detailed method and does not include oil drift calculations. Use of this method presupposes that one can take as a starting point a “reference assessment” containing previously carried out oil dispersion simulations that apply to the influence area in question’ (DNV 2007, 2). The reference assessment is considered adequate if it is judged as providing more conservative results than the more detailed assessment types would have done.

An exposure-based assessment ‘provides a measure of potential environmental risk within a limited area, based on probabilities of oil pollution and presence of vulnerable and valuable resources. The analysis includes oil dispersion calculations and calculates the risk of damage to vulnerable resources in affected areas’ (DNV 2007, 2). For a given 10×10 km square, the frequency of damage in consequence category D_i can then be determined as

$$f(D_i) = f_0 P(\text{exposure}|\text{release}) P(D_i|\text{exposure,release}), \quad i = 1,2,3,4,$$

where f_0 is the release frequency, P(exposure|release) the probability of exposure of the square given a release, and P(D_i|exposure,release) the probability of consequence category D_i given a release and exposure. If an exposure-based assessment shows that the potential environmental risk is above the risk acceptance criterion, a damage-based assessment should be carried out.

A damage-based analysis 'calculates the degree of damage and recovery time for selected species, populations and habitats that are considered to be good indicators of environmental risk for acute oil spills. These are designated VEC (Valued Ecosystem Component)' (DNV 2007, 2). Restoration here refers to the situation before the exposure, or to a new normal situation when taking natural variation into account. The damage calculations differ, depending on whether these are done for a VEC population or a VEC habitat and also depending on the type of population.

The risk assessment methodology described in the guideline consists of the following main steps (DNV 2007, 11):

(1) 'Define risk acceptance criteria
(2) Establish an activity description
(3) Establish probability estimate of unwanted event
(4) Establish a sufficient number of probable combinations of release durations and rates in the environmental risk assessment
(5) Oil drift simulations
(6) Perform damage calculations
(7) Calculate environmental risk.'

The three types of assessment defined above are described as increasingly comprehensive and decreasingly conservative. Steps 1 through 4 above are common to all three types of assessments, step 5 is performed in both exposure-based and damage-based assessments but not in reference-based assessments, and step 6 is performed only in damage-based assessments.

The ERA method described in the guideline is in many respects a well-defined and advanced type of analysis. While the main focus of the present paper is on the foundations of the method with respect to how risk and uncertainty is conceptualised and described, some overall comments on the strengths and weaknesses of the guideline and method can however be made: In terms of the bow-tie model, the ERA guideline is strongly focused on the consequence side. There is detailed and sophisticated modelling of dispersion, ecotoxicology and recovery given a release, and the insights gained by this is clear. There is, however, no modelling of the causal side. A set of 'standard' initiating events (blowout, process leak, etc.) are defined and frequencies for these are required to be established using historical data. As such, there is no reflection of what influences the occurrence of releases, e.g. physical climate factors or safety climate (indicators).

3.2. Risk

Risk is defined with slight variations in wording at different points in the ERA guideline. The three variations given are:

> 'Risk is the combination of probability of damage to occur and the severity of this damage' (DNV 2007, 7)
> 'Risk – In this context, a combination of probability of environmental damage to occur and the severity of this damage' (DNV 2007, 11)
> 'Environmental risk is a function of the probability and consequences of a discharge' (DNV 2007, 29)

In all three instances, risk is defined in terms of the probability and (severity) of consequences, which is in line with the old PSAN definition as well as the with the SRA risk description definition a); cf. Section 2. Nonetheless, the following statement can be interpreted to be in line with the new PSAN definition; cf. Section 2 (DNV 2007, 3):

> 'Unfortunately, no technologically advanced activity can be performed without some risk. […] There will always be some uncertainty with respect to which consequences an activity can lead to.'

The above statement, however, is not followed up in the sense that the guideline neither explicitly states nor implicitly indicates that a distinction is made between the overall qualitative definition of risk as a concept, and specific risk metrics/descriptions, as is done in the SRA glossary; cf. Section 2. The following statement indicates what is considered the key components of the risk description according to the guideline (DNV 2007, 12):

> 'Risk assessment is to calculate the probability of events combined with the extent of damage of these.'

Hence, according to the guideline, the concept of risk and its measurement/description seem to coincide. The use of the term 'potential' in the phrase 'potential (environmental) risk' in the description of exposure-based assessment is presumably intended to reflect the conservativeness of this approach, although the meaning of 'potential risk' is not made clear in the guideline.

Knowledge is not acknowledged as a key component of the risk description, and only probability is used as a measure of uncertainty. In the following subsection, we investigate the approach to uncertainty treatment in the guideline.

3.3. Uncertainty

The ERA guideline explicitly addresses uncertainty in one of its subchapters, entitled 'Treatment of uncertainty'. The chapter starts by pointing out that the numbers produced are not to be understood as exact measures of environmental damage, but only as best estimates based on current knowledge and data from previous oil discharges, and that new knowledge could change the measure of environmental risk at a later stage. The guideline also states that uncertainty reduction is sought as much as possible in the ERA, through strategies such as the use of best knowledge, as well as conservative values, whenever exact knowledge is missing. Regarding conservative values, the ERA guideline prescribes that (DNV 2007, 19):

> 'The main principle of the guidelines is that neutral or little conservative calculations require thorough analyses. When simplifications are introduced in models and descriptions of uncertainty, these shall translate into conservative direction, and the judgements that the simplifications are based on shall be documented.'

Nonetheless, although the use of conservative values or, more generally, conservative assumptions is a main uncertainty treatment strategy in the guideline, no guidance is given on how to assess the bias and uncertainty related to the assumptions that are made.

Beyond the strategies of best knowledge and conservative values, the guideline suggests highlighting uncertainty, using probability distributions on the different damage categories for which environmental risk is calculated. Probability distributions are also described as a common way of handling the uncertainty that is 'present in all model calculations steps' (DNV 2007, 53). For example, probability distributions are prescribed for discharge durations and discharge points. In the example calculations shown in the guideline, probability distributions are established on the discharge duration categories 0-2 days, 2-5 days, 5-14 days, 14-30 days, and 30-40 days, as well as on the discharge points ‘surface’ and ‘subsurface’.

The subchapter on the treatment of uncertainty ends by listing the most important uncertainty factors in ERAs and describing how these may be taken into consideration in the analysis. The uncertainty factors mentioned are blowout frequencies, blowout scenarios (the sequence of events of a blowout, given its occurrence, including rates and durations), oil type and properties, oil drift modelling (uncertainty related to oil drift and disintegration), uncertainty related to the distribution of vulnerable resources, and uncertainty in the calculation of damage extent. The different strategies that are mentioned for handling these are technical risk assessment, conservativism, running a large number of simulations, modelling, regular data updates, effect and damage keys (i.e., dose-response functions), and distributions over consequence categories.

The guideline hence gives some sound advice concerning uncertainty representation and does so by explicitly mentioning the concept of knowledge. The conceptual foundation of the recommendations of the guideline can, however, be strengthened and aligned with the new PSAN risk definition.

For example, concerning uncertainty representation, the type of probabilities used is not specified. The term ‘probability estimate’ used throughout the guideline document can be seen as an indication that the intended interpretation is frequentist probabilities, which is a measure of variation (sometimes referred to as aleatory, or stochastic uncertainty) and which is interpreted as the fraction of times an event occurs if the situation is repeated (hypothetically) an infinite number of times (e.g., Aven 2012a). On the other hand, lack of knowledge (sometimes referred to as epistemic uncertainty) is typically represented using subjective probabilities, possibly interval valued. A subjective probability of an event A, equal to, say, 0.3 can be interpreted to mean that the event A is judged, by the person assigning the probability, to be equally likely as the 'standard event' of drawing a red ball from an urn containing three red and seven non-red balls (e.g., Aven 2012a).

No distinction between these measures (frequentist and subjective probability) is made in the ERA guideline. There is, in fact, no clarification (e.g., definition) of the concept of uncertainty. Consider the following statements from the guideline:

> 'Risk assessments are conducted to ensure that uncertainty is reduced when decisions regarding the activity are to be made.' (DNV 2007, 3)
> 'It is completely possible to analyse environmental risk without having all the information, but uncertainty in the analysis can be reduced with increasing information access.' (DNV 2007, 14)
> 'In the environmental risk assessment, one seeks to reduce the uncertainty as much as possible.' (DNV 2007, 53)

These statements indicate that the uncertainty referred to is epistemic uncertainty, considering the argument made that uncertainty can be reduced by increased information and that epistemic uncertainty is commonly referred to as reducible uncertainty and aleatory uncertainty as irreducible uncertainty (e.g., Helton and Burmaster 1996). On the other hand, although the guideline does refer to different forms of variation (e.g., 'variation', 'natural variation', 'variation in time and space', 'seasonal variation'), the following statements show that the term 'uncertainty' is also used to refer to variation and not just epistemic uncertainty:

> 'Uncertainty in drift paths is taken into account by running many simulations (for example 3600 per year) under different weather conditions, and developing statistics.' (DNV 2007, 54)

Finally, the guideline refers to both 'current knowledge' and 'best knowledge';

however, neither the meaning of knowledge nor the role of knowledge and its strength in the risk description is clarified.

4. A framework for conceptualising environmental risk and its description in line with the new uncertainty-based risk definition

In this section, we present a framework for conceptualising risk and its description that is consistent with the new Petroleum Safety Authority Norway (PSAN) risk conceptualisation and show how it can be adapted to the setting of environmental risk assessment (ERA). The framework consists of a conceptual basis, described in Section 4.1, and a scheme for assessment of the bias of uncertain assumptions described in Section 4.2.

4.1. Risk conceptualisation and description

The conceptual basis of the framework described below follows the SRA glossary (SRA 2018) (cf. Section 2) and Aven (2012b) closely; see also Aven (2012a; 2014). The starting point is some future activity, for example, the operation of a system such as an oil and gas platform in the Arctic. Risk is defined in terms of the consequences of this activity, where the consequences are with respect to something humans value and may be seen in relation to some reference values. The focus will typically be on negative (undesirable) consequences, such as environmental damage resulting from an oil spill from the platform. In the case of an oil spill, the reference value could be an objective stated by the operating company that there should be no oil discharges beyond planned, operational discharges.

Let C denote the future consequences of the activity in question and let U represent the condition that a state of intersubjective uncertainty exists about C. Then we can write risk = (C,U) to formalise the PSAN definition of risk as ‘the consequences of the activities, with associated uncertainty'; cf. Section 2. The consequences arise from a set of risk sources (RS) which give rise to a set of events/hazards (A). A risk source is here understood as an 'element (action, sub-activity, component, system, event, …) which alone or in combination with other elements has the potential to give rise to some specified consequences (typically undesirable consequences)' (SRA 2018, 10).

In a risk assessment, the risk analyst specifies risk sources, events/hazards and consequences that it is thought could occur during the activity for which the risk assessment is carried out. Let C' denote these specified consequences, RS' the specified risk sources, and A' the specified events/hazards. In a risk assessment context, we need a way of conceptualising the idea of unforeseen risk sources, events/hazards and consequences, and the distinction between RS and RS', A and A', and C and C' allows for just this. This set-up can also be extended to cover past risk sources, events/hazards and consequences, (RS'',A'',C''), that are known to have taken place in the past. The specification of (RS',A',C') will typically be based at least partially on an identification of what has occurred in the past and on a subsequent evaluation of the relevance of these in relation to the activity for which the risk assessment is being carried out. Additionally, various creative processes may lead to inclusion into (RS',A',C') of potential consequences that have not (or at least are not known to have) taken place in the past but which, based on the existing phenomenological understanding of the activity in question, are judged as possible.

Next, the risk analyst assesses the uncertainties related to (RS',A',C'), representing the assessed uncertainty using some uncertainty measure, Q. The specification of (RS',A',C') and Q is based on some background knowledge, K, which is also part of the risk description. The SRA glossary distinguishes between two types of knowledge (SRA 2018, 8): ‘know-how (skill) and know-that of propositional knowledge (justified beliefs)’. Both types are relevant in relation to performing a risk assessment. However, propositional knowledge is most relevant to consider in relation to the risk description per se, as the consequences specified in the risk description can essentially be seen as a set of propositions. As pointed out by one of the referees of this paper, also a third form, know-about, or acquaintance knowledge (cf. Lemos 2007), is relevant in relation to bias. For example, an expert assigning a probability may be influenced by availability heuristics, which essentially refers to the ease with which similar events can be retrieved from memory (e.g. Aven 2012a). The basis for forming propositional knowledge in the form of justified beliefs will typically be data and information. In a risk assessment, these beliefs are often expressed in the form of assumptions (Aven 2014). Uncertain assumptions and their bias will be considered in detail in Section 4.2.

The typical uncertainty measure is probability, P, i.e. using Q = P. However, conceptualising the risk description in terms of a general measure Q also allows for other quantitative measures, as well as to qualitative characterisations. Non-probabilistic quantitative measures include belief and possibility functions in evidence and possibility theory, respectively, as well as imprecise/interval probability (e.g., Aven et al. 2013). One type of qualitative characterisation is that resulting from assessing and characterising the strength of knowledge (SoK) that the assignment of the quantitative uncertainty measure is based on, for example, using the NUSAP scheme mentioned in Section 2. The result is a semi-quantitative uncertainty measure comprising a quantitative measure, say probability, P, along with the qualitative strength of knowledge characterisation, SoK, i.e. using Q = (P,SoK). Another scheme for assessing the strength of knowledge consists of labelling the knowledge as strong if all the following criteria – whenever they are relevant – are satisfied (Flage and Aven 2009, 14):

- ‘The phenomena involved are well understood; the models used are known to give predictions with the required accuracy.
- The assumptions made are seen as very reasonable.
- Much reliable data are available.
- There is broad agreement among experts.’

If the opposite is the case for at least one of the criteria, e.g. if the assumptions made represent strong simplifications, the knowledge is labelled as weak. For in-between cases, the strength of knowledge is labelled as moderate (Flage and Aven 2009).

Within the framework described, uncertainty is understood fundamentally as lack of knowledge (i.e., as epistemic uncertainty) (cf., e.g., Apostolakis 1990; Aven 2012a; Winkler 1996). The U component in the risk concept (C,U) denotes the condition that there is intersubjective lack of knowledge about what the future consequences C will be. Furthermore, the uncertainty measure Q may be subjective probability, measuring and expressing degree of belief. Frequencies expressing rates of occurrence and thus measuring variation are treated as uncertain quantities on which an uncertainty measure (e.g., subjective probability distributions) may be assigned.

The risk description can thus be conceptualised as (RS’,A’,C’,Q,K). The relationship between risk sources, events/hazards and consequences in terms of exposure is illustrated in Figure 1.

[Figure 1 near here]

In the following, we provide some motivation for distinguishing between future consequences C (of the activity considered) and specified consequences C’ (in the risk assessment of that activity), as well as some examples showing how the generic framework described above can be adapted to the ERA setting.

Table 1 shows some concrete examples of the different main and sub-components of the generic risk description (RS’,A’,C’,Q,K), at high and low levels of detail, for an Arctic ERA setting. The sets of examples in Table 1 are not complete. For instance, the frequency of blowout and the probability of barrier failure are just examples of (low-level) uncertainty measures. Similar uncertainty measures need to be established for the realisation of all the specified risk sources, for the occurrence of all the specified events/hazards, and for the outcome of all the specified consequences. Previously occurred risk sources, events/hazards, and consequences, as well as data, can be thought of as evidence, leading to knowledge understood as justified beliefs (cf. SRA 2018), to a large extent formulated as models and assumptions. For example, a Bayesian Belief Network (BBN) can be used to represent and analyse the relation between cold climate and process leaks. The BBN model then reflects the (justified) beliefs that the analyst has about how cold climate factors, such as icing, could contribute to the occurrence of process leaks. The BBN model will be based on some assumptions and implies the use of probability as the quantitative uncertainty measure. Note that, as pointed out by one of the reviewers of the present paper, the nature of the three sub-components of the risk description are different. For the specified risk sources, events/hazards and consequences (RS’,A’,C’), the sub-components are linked sequentially, with consequences arising as a result of exposure to events/hazards, which again arise due to exposure to risk sources. For the uncertainty measure, the sub-components are alternatives, i.e., the risk analyst can use quantitative and/or qualitative measures of uncertainty. And for the background knowledge, the sub-components are different sources of knowledge, not all of which may be available. In Table 1, the specific examples of the high- and low-level specified events/hazards and consequences, as well as the high-level previously occurred events/hazards, are based on the ERA guideline (DNV 2007).

[Table 1 near here]

Previously occurred risk sources, events, and consequences thus refer to the factual evidence about relevant past occurrences, for example the Ekofisk (1977) blowout and the Statfjord A oil leakage mentioned in Table 1. How good, or vague, or relevant, the knowledge of these past occurrences is evaluated as part of the strength of knowledge evaluation; cf. the measure of uncertainty (Q).

A central component of the risk description in a quantitative risk assessment is the set of – typically probabilistic – risk metrics used to characterise the risk level. Suppose that the severity of the specified consequences (C’) of the activity is characterised by an (uncertain) quantity Y. Then, a relatively general formulation of such a risk metric, here denoted R, is

$$R = bE[Y|K], \tag{1}$$

where b is a normalising constant and K, as above, is the background knowledge on which the risk description is based. The risk metric prescribed in the ERA guideline is the frequency of some specified damage extent D_i to some environmental component H, i.e.,

$$f(\text{damage extent } D_i \text{ on environmental component } H).$$

The frequency above can be restated as $E[Y(D_i,H)|K]$, where $Y(D_i,H)$ is the number of times in a specified time period, typically a year, that an event with damage extent D_i to the environmental component H occurs. The above frequency is thus a special case of the risk metric R, with b = 1 and with Y as a function of D_i and H.

When calculating risk metrics such as R, typically, several assumptions must be made. As described by Flage & Berner (2017), risk assessment assumptions can be made as a simplification or due to lack of knowledge. To highlight the dependence of the assumptions, which in Equation (1) is tacitly understood to be part of K, the risk metric R in Equation (1) can be restated as

$$R(x_0) = bE[Y|X = x_0, K], \tag{2}$$

where X denotes some quantity (possibly vector-valued) about which the assumption(s) is made and x_0 is the (base case) value that is assumed. In Equation (2), K is tacitly understood as $\{K \backslash X = x_0\}$, i.e. as the background knowledge that remains when the assumptions are removed. It could be argued that, ideally, it would be desirable to determine a risk metric unconditional on assumptions, using the law of total expectation; i.e., by determining

$$E[Y|K \backslash X = x_0] = \int E[Y|X = x]dF(x),$$

where F is a probability distribution on X. In practice, however, this is often difficult to do, as establishing the probability distribution F typically involves making further assumptions; see the discussion in Berner & Flage (2016). Instead, assumptions are often made which are conservative, as prescribed by the ERA guideline. The degree to which an assumption is conservative versus optimistic can be referred to as its bias. In the next section, we present a scheme for assessing the bias of uncertain assumptions.

4.2. A scheme for assessing uncertain assumptions and their bias

Based on the concept of assumption deviation risk, as proposed by Aven (2013), Berner & Flage (2016) derive a classification scheme for uncertain assumptions. The purpose of the scheme is to support decision-making on strategies for treating the uncertainty related to assumptions made in a quantitative risk assessment. In this context, assumptions can be understood as 'conditions/inputs that are fixed in the assessment, but which are acknowledged or known to possibly deviate to a greater or lesser extent in reality' (Berner and Flage 2016, 46). Table 2 shows how different assumption settings are obtained by classifying as either low or moderate/high, i) the belief in deviation from an assumption that has been made, and ii) the sensitivity of the risk metric (with respect to deviations in the assumption); and classifying as either strong or moderate/weak, iii) the strength of knowledge involved (evaluated, for example, according to the criteria described in Section 4.1). Berner & Flage (2016) link the different settings in Table 2 to different uncertainty treatment strategies. For example, Setting I assumptions are classified as non-critical and documented in the risk assessment but not subject to further follow-up in terms of uncertainty treatment. For Setting V assumptions, on the other hand, alternative assumptions are formulated, and probabilities are assigned to these so that the unconditional risk metric can be determined using the law of total expectation.

[Table 2 near here]

Berner & Flage (2017) suggest how to create risk management strategies for uncertain assumptions based on the settings in Table 2 as well as on aspects from the so-called assumption-based planning framework by Dewar (2002). Such strategies are outside the scope of the present paper, which is focused on the analytical treatment of uncertain assumptions.

The classification scheme proposed by Berner & Flage (2016) only considers 'unfavourable' deviations, i.e. deviations that would lead to worse conditions than that assumed in the risk assessment. While such deviations will often be of greater concern to a decision-maker than 'favourable' deviations, where conditions turn out to be better than was assumed, the degree of conservativism versus optimism underlying a risk assessment also provides useful decision support. Based on this premise, in the present paper, we extend the existing scheme to consider both potential 'unfavourable' as well as potential 'favourable' deviations in assumptions. The extended scheme is described in the following, using the following example assumptions as an illustration:

- B1: Oil drift in icy waters will behave as (i.e., is modelled as) oil drift in non-icy waters.
- B2: A relief well will take at most 100 days to drill.
- B3: The set of identified unwanted initiating events is complete.
- B4: The set of identified scenarios is complete.
- B5: Existing emergency preparedness measures have no effect (i.e., are not accounted for in the modelling).

Assumption B1 is judged to be a conservative assumption, since the inclusion of ice in the modelling set-up is expected to result in a lower drift speed and hence a smaller influence area. Relative to the assumption made, there is a low degree of belief in deviation in an unfavourable direction (higher drift speed and greater influence area) and a moderate/high degree of belief in deviation in a favourable direction (lower drift speed and smaller influence area). Moreover, the sensitivity of the risk metric to changes in the drift speed and influence area is classified as moderate/high for deviations in both directions. Finally, all these judgements are made against an otherwise strong background knowledge (accurate models, much relevant data, and experts agree). Table 3 shows the resulting classification for assumption B1, as well as for the other example assumptions, which are described in the following.

[Table 3 near here]

Assumption B2 relates to the maximum time to drill a relief well that is reflected in the probability distribution of the duration of such a drilling operation. That is, for a set of increasing potential drilling durations $(z_1,z_2,\ldots,z_m)$, the assumption B2 relates to the value chosen for z_m. Hence, there is no favourable deviation potential. The assumption states that the actual drilling duration Z will be less than z_m. Then, if $0 \leq Z \leq z_m$, the assumption is fulfilled and, if $Z > z_m$, the assumption is violated in an unfavourable direction. There is, however, a low degree of belief that Z exceeds z_m, and the sensitivity of the risk metric with respect to such an exceedance is also low. These judgements are, however, considered to be based on moderate/weak knowledge.

Assumptions B3 and B4 are similar to assumption B2, in the sense that there is no favourable deviation potential. The assumption B3 (B4) states that the actual event(s)/hazard(s) A will be contained in the set of events/hazards A' described in the risk assessment. Then, if A is contained in A', the assumption is fulfilled; otherwise, the assumption is violated in an unfavourable direction. Assumption B3 relates to initiating events, i.e. to broad overall categories of event types, such as a blowout, process leak, riser leak, etc. Assumption B4, on the other hand, relates to the detailed scenarios in which the initiating events occur. For example, a process leak can occur in numerous ways, e.g. as a result of dropped objects, material fatigue, or erroneous process operator actions. After decades of offshore petroleum exploration and production activities worldwide, there is a low degree of belief, based on knowledge that is judged as strong, that a surprising event should occur that is not covered by the 'standard' set of initiating events and thus lead to a violation of assumption B3. It is, however, judged that the contribution to the overall risk level from any new initiating event, and thus the sensitivity of the risk measure with respect to the addition of such an event, will be at least moderate, since an initiating event is understood as a broad overall category of event types. It is also acknowledged that all the detailed ways in which the different initiating events may occur are not necessarily covered by the set of scenario descriptions in the risk assessment. The degree of belief in deviation from assumption B4 is accordingly classified as moderate/high. The sensitivity is, however, still classified as low, as the contribution to the overall risk level from any single new specific detailed scenario, and thus the sensitivity of the risk measure with respect to the addition of such a scenario, is expected to be low. The knowledge supporting these judgements is judged as moderate/weak.

Assumption B5 is opposite to assumptions B2, B3, and B4, in the sense that there is no unfavourable deviation potential. Assumption B5 states that the emergency preparedness measures that are in place and which are planned to be implemented if a discharge occurs will have no effect (i.e., the modelling in the risk assessment is performed as if these measures were not in place). In terms of deviations in an unfavourable direction, both the belief in deviation and the sensitivity are thus classified as not applicable (NA), with a strong knowledge supporting these classifications. In terms of deviations in a favourable direction, both the belief in deviation and the sensitivity are classified as moderate/high, with strong knowledge supporting these classifications, as the (highly costly) emergency preparedness measures would not have been implemented if there were an unsupported or low belief in their effect or efficiency.

Table 4 and Table 5 illustrate how assumptions where the associated knowledge is strong (Table 4) or moderate/weak (Table 5), respectively, can be transferred from Table 3 and ranked, thus resulting in a spectrum of assumptions ranging from strongly conservative to strongly optimistic. Note that Table 4 is a transformation of the classifications of the assumptions B1, B3 and B5 in the columns 3 and 5 of Table 3; whereas Table 5 is a transformation of the classifications of the assumptions B2 and B4 in the columns 4 and 6 of Table 3. In the following, we describe three possible usages of such an assumption bias ranking scheme.

[Table 3 near here]

[Table 4 near here]

[Table 5 near here]

Firstly, in the risk analysis phase, the ranking scheme could be used as a screening method to i) induce re-thinking of initially suggested assumptions, if these are classified in, say, any of the ‘optimistic’ categories; and to ii) create strategies for how to treat the uncertainty related to the final assumptions in the risk assessment. Such strategies could be formulated along the lines of the strategies suggested by Berner & Flage (2016), as described at the beginning of Section 4.2. Secondly, in preparation for the risk evaluation phase, the ranking scheme could be used to formulate risk acceptance criteria in a format that extends beyond probabilistic risk metric thresholds. For example, the decision-maker could specify that the risk is acceptable only if:

- the probabilistic risk metric is below a threshold r_0; and,
- for assumptions related to strong knowledge, there are no assumptions in any of the ‘optimistic’ categories, or in the ‘Neutral – Strongly inaccurate’ category; and,
- for assumptions related to moderate/weak knowledge, there are no assumptions in any of the ‘optimistic’ or ‘neutral’ categories.

Thirdly, in the risk management phase, the ranking of the assumptions could be used to follow up the different assumptions when the activity in question is carried out. For example, the following types of strategies could be implemented:

- Assumptions in the ‘conservative’ categories: Verify at regular intervals during the execution of the activity.
- Assumptions in the ‘neutral’ categories: Monitor closely during the execution of the activity.
- Assumptions in the ‘optimistic’ categories: Monitor closely and implement measures to increase the belief in favourable deviations from the assumptions and to decrease the belief in unfavourable deviations.

In the next section, we discuss the framework and the assumption bias classification scheme described above.

5. Discussion

The framework described in Section 4.1 contains suggestions for how to strengthen the conceptual basis and clarity of the ERA guideline in particular, as well as of ERAs in general. Also, an associated scheme for assessing the bias of uncertain assumptions in quantitative risk assessments is described in Section 4.2. In this section, we discuss: the implications for the practice of ERAs (as specified by the guideline) of implementing the framework; using the distinction between risk sources, (initiating) events/hazards, and consequences, as well as between high-level and low-level consequences, to compare risk related to similar but not identical activities; and some limitations of the paper.

Implementing the framework described in Section 4 would bring the practice of ERA, as prescribed by the guideline, in line with recent thinking about risk as adopted and prescribed by, amongst others, the PSAN, SRA, and ISO; cf. Section 2. Some key practical implications would be the need for the following: to clarify the meaning of risk, variation, uncertainty, probability, and knowledge; and to implement methods for assessing the strength of knowledge supporting probabilities, as well as principles for evaluating these assessments together with the probabilities when making judgements about risk acceptance. The latter would mean a less strong focus on single-valued risk acceptance criteria compared to today. The following is one suggestion for how a procedure for judging risk acceptance might look, when also considering the strength of knowledge (Aven 2013, 141):

- ‘If risk is found acceptable according to probability with large margins, the risk is judged as acceptable unless the strength of knowledge is weak (in this case the probability based approach should not be given much weight).
- If risk is found acceptable according to probability, and the strength of knowledge is strong, the risk is judged as acceptable.
- If risk is found acceptable according to probability with moderate or small margins, and the strength of knowledge is not strong, the risk is judged as unacceptable and measures are required to reduce risk.
- If risk is found unacceptable according to probability, the risk is judged as unacceptable and measures are required to reduce risk.’

The separation into i) risk sources, events/hazards, and consequences, and ii) high-level and low-level elements of these, could be useful for comparing risk related to similar but not identical activities, by providing insights on what is common in terms of risk and what is specific to the individual activities. Such a comparison would be particularly useful if the experience and knowledge related to one of the activities is stronger than that related to the other, as the insights gained from such a comparison could form the basis for an opinion on the need for risk assessment method development.

As an example, take offshore petroleum activities in the Arctic versus in the North Sea. The Norwegian petroleum industry has several decades' worth of experience operating in the North Sea and much less so in the Barents Sea and further north. This raises the question of whether other ('new') types of risk sources, events/hazards and consequences are possible in the Arctic compared to in the North Sea (and, vice versa, whether some types are only possible in the North Sea but not in the Arctic).

Table 6 illustrates such a comparison, where a separation is made between risk sources, events/hazards, and consequences. The following inferences can be drawn from the table:

[Table 6 near here]

Firstly, several risk sources are common to both the North Sea and the Arctic, e.g. ship traffic, fishing vessels, and subsea templates. However, there are also risk sources that are specific to the Arctic, e.g., cold climate, long distances, and limited satellite coverage. Moreover, some risk sources are specific to the North Sea, e.g., Condeep type platforms. In terms of risk assessment method development, such an observation could lead to the conclusion that there is a need to: i) carry out a risk identification process, based on the identified 'new' risk sources, to see whether any of these could lead to 'new' types of events/hazards or consequences; and ii) develop new models linking the 'new' risk sources to the identified events/hazards and consequences. For example, as described in Section 1, the development of a new methodology for calculating environmental risk in the marginal ice zone (DNV GL & Akvaplan-niva 2014) stemmed from a recognition of the need for new analytical practice in the Arctic: in this case the presence of the ‘new’ risk source ‘sea ice’ in the potential influence area of blowouts.

Secondly, all the high-level events/hazards listed in the ERA guideline (blowout, process leak, pipeline leak, etc.), and thus commonly studied in ERAs of activities in the North Sea, are also relevant for ERAs of activities in the Arctic. The high-level event ‘tanker accident’ includes any number of lower-level events, for example, the events ‘tanker collision with iceberg’ and ‘tanker collision with Condeep platform’, which are only relevant to the Arctic and to the North Sea, respectively, and the former of which can be identified based on taking together the ‘existing’ (initiating) event ‘tanker accident’ and the ‘new’ risk source ‘iceberg’.

Thirdly, as for the high-level events, all the key quantities defined and studied in the ERA guideline and characterising high-level consequences, are also relevant for ERAs of activities in the Arctic. The quantity ‘fraction of population lost’ is an example of such a quantity, which taken together with the Arctic environmental component ‘polar cod’ could lead to the specification of the lower-level consequence ‘40% of polar cod population lost’, which is only relevant to the Arctic.

Note that a comparison as described in the preceding paragraph only relates to the risk source, event/hazard and consequence component of risk, i.e., to (RS,A,C). Greater risk related to one activity over another would, for example, thus not be revealed by such a comparison, as these concepts also involve the uncertainty dimension. However, a comparison as indicated above could form a systematically derived basis for assessing risk.

The scheme described in Section 4.2 has been developed and applied with assumptions in mind. The scheme assesses the bias of uncertain assumptions. Like assumptions, also models are typically fixed through choice in the risk assessment. The assessment scheme should in principle also be applicable to assess the bias of models, though to elaborate on this idea, further development and testing is needed in future research.

Some limitations of the present paper can be pointed out. Firstly, a large-scale case study implementation of the described framework would be useful in terms of showing extensively and in detail the application and implications of the described framework and assumption assessment method. The paper is, however, focused on developing the foundations of the framework, supported by examples and illustrations from the context of environmental risk assessment of petroleum activities in the Arctic. Both the examples used during the framework presentation and discussion, as well as most of the assumptions used as examples in Section 4.2, are, however, inspired by conditions considered and assumptions made in real ERAs of offshore petroleum activities. Secondly, a brief review of the overall ERA process/method as presented in Section 3.1, of course, cannot do full justice to the comprehensive process/method described in detail in the ERA guideline. The focus of the present paper is the risk conceptualisation and treatment of uncertainty in the ERA guideline; the review of the overall ERA process/method is included in the paper to place the focused and detailed analysis of the two studied issues in a broader context. The ERA guideline methodology is planned to be replaced by a methodology called ERA Acute. Although the new ‘ERA Acute’ methodology is more sophisticated in the environmental (consequence) modelling, the recommendations in the present paper still stand as the new methodology it is based on the same consequence-probability risk conceptualisation as in the reviewed guideline. Finally, as commented by one of the referees of the present paper, there is little evidence available about the ‘goodness’ of the large number of ERAs being carried out in the industry. Whether the seldom nature of mega-disasters is due to the ERAs being carried out, or because of a general and appropriate wariness within the industry, is an open question and a worthwhile question for future research.

6. Conclusions

In the present paper, we first review and discuss an industry guideline for environmental risk assessment (ERA) in the Norwegian petroleum industry, before presenting a framework for conceptualising and describing risk in an ERA context, as well as a scheme for assessing the bias of uncertain risk assessment assumptions.

The review and discussion of the ERA guideline focuses on the concepts of risk and uncertainty and results in the overall conclusion that the conceptual basis of the guideline can be strengthened. Firstly, the conceptualisation of risk used is no longer in line with the definition of risk adopted by the Petroleum Safety Authority Norway (PSAN), as well as by other actors and documents in the field of risk analysis, such as the Society for Risk Analysis (SRA) and the ISO 31000 standard on risk management. Secondly, although the guideline gives some sound advice regarding the treatment and representation of uncertainty, there is room for greater conceptual clarity on the key concepts of uncertainty, variation, probability, and knowledge, as well as on the treatment of assumptions with respect to their bias and uncertainty.

The described framework contains suggestions for how to strengthen the conceptual basis and clarity of the ERA guideline in particular, as well as of ERAs in general. Key characteristics of the framework are as follows: a distinction between risk as a concept and the description or measurement of this concept (including risk metrics); the inclusion of a general uncertainty measure, as well as knowledge, as main components of the risk description, in addition to specified consequences; a decomposition of these main components into more operational sub-components at high and low levels; and a relatively general risk metric formulation, linking the quantitative risk characterisation to associated assumptions. Building on and extending previously developed schemes for assessing uncertain assumptions in quantitative risk assessment, a new scheme for assessing the bias (i.e., conservativeness versus optimism) of assumptions is suggested.

In terms of the practical implications of implementing the framework when performing ERAs (as specified by the guideline), there would be a need to clarify the meaning of uncertainty, variation, probability, and knowledge, and to implement methods for assessing the strength of knowledge supporting the probabilities, as well as procedures for evaluating these assessments, together with the probabilities, when making judgements about risk acceptance. The latter would mean a less strong focus on single-value risk acceptance criteria than the ERA guideline prescribes. Finally, separating the concept of consequences of an activity into risk sources, events/hazards, and consequences, as well as between high-level and low-level consequences, is shown to be potentially useful for comparing risk related to similar but not identical activities.

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References

Apostolakis, George. 1990. ‘The Concept of Probability in Safety Assessments of Technological Systems’. *Science* 250 (4986): 1359–64. https://doi.org/10.1126/science.2255906.

Aven, Terje. 2012a. *Foundations of Risk Analysis*. John Wiley & Sons.

———. 2012b. ‘On the Link between Risk and Exposure’. *Reliability Engineering & System Safety* 106 (October): 191–99. https://doi.org/10.1016/j.ress.2012.06.004.

———. 2013. ‘Practical Implications of the New Risk Perspectives’. *Reliability Engineering & System Safety* 115 (July): 136–45. https://doi.org/10.1016/j.ress.2013.02.020.

———. 2014. *Risk, Surprises and Black Swans : Fundamental Ideas and Concepts in Risk Assessment and Risk Management*. Routledge. https://doi.org/10.4324/9781315755175.

Aven, Terje, Piero Baraldi, Roger Flage, and Enrico Zio. 2013. *Uncertainty in Risk Assessment: The Representation and Treatment of Uncertainties by Probabilistic and Non-Probabilistic Methods*. John Wiley & Sons.

Backhaus, Thomas, and Michael Faust. 2012. ‘Predictive Environmental Risk Assessment of Chemical Mixtures: A Conceptual Framework’. *Environmental Science & Technology* 46 (5): 2564–73. https://doi.org/10.1021/es2034125.

Berner, Christine L., and Roger Flage. 2016. ‘Strengthening Quantitative Risk Assessments by Systematic Treatment of Uncertain Assumptions’. *Reliability Engineering & System Safety* 151 (July): 46–59. https://doi.org/10.1016/j.ress.2015.10.009.

———. 2017. ‘Creating Risk Management Strategies Based on Uncertain Assumptions and Aspects from Assumption-Based Planning’. *Reliability Engineering & System Safety*, Special Section: Applications of Probabilistic Graphical Models in Dependability, Diagnosis and Prognosis, 167 (November): 10–19. https://doi.org/10.1016/j.ress.2017.05.009.

Bogen, Kenneth T., and Robert C. Spear. 1987. ‘Integrating Uncertainty and Interindividual Variability in Environmental Risk Assessment’. *Risk Analysis* 7 (4): 427–36. https://doi.org/10.1111/j.1539-6924.1987.tb00480.x.

Brand, Kevin P., and Mitchell J. Small. 1995. ‘Updating Uncertainty in an Integrated Risk Assessment: Conceptual Framework and Methods’. *Risk Analysis* 15 (6): 719–29. https://doi.org/10.1111/j.1539-6924.1995.tb01344.x.

Dewar, James A. 2002. *Assumption-Based Planning: A Tool for Reducing Avoidable Surprises*. Cambridge University Press.

DNV. 2007. ‘Method for environmental risk assessment [Metode for miljørettet risikoanalyse; in Norwegian only]’. 2007–0063. https://www.norskoljeoggass.no/globalassets/dokumenter/miljo/mira-2007.pdf.

DNV GL & Akvaplan-niva. 2014. ‘Development of Methodology for Calculations of Environmental Risk for the Marginal Ice Zone’. 2014–0545. https://www.norskoljeoggass.no/contentassets/ded3880a762c45e79c7aaf548adb93fc/environmental-risk-methodlogy-mira---miz.pdf.

EPA. 2003. ‘A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information’. EPA 100/B-03/001. https://www.epa.gov/sites/production/files/2015-01/documents/assess2.pdf.

———. n.d. ‘Risk Assessment’. In . Accessed 13 September 2017. https://www.epa.gov/risk.

Ferson, S., and T. F. Long. 1995. ‘Conservative Uncertainty Propagation in Environmental Risk Assessments’. In *Environmental Toxicology and Risk Assessment*, 3:97–110. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/STP12686S.

Flage, Roger, and Terje Aven. 2009. ‘Expressing and Communicating Uncertainty in Relation to Quantitative Risk Analysis’. *Reliability & Risk Analysis: Theory & Application* 2 (13): 9–18.

Flage, Roger, and Christine L. Berner. 2017. ‘Treatment and Communication of Uncertain Assumptions in (Semi-)Quantitative Risk Assessments’. In *Knowledge in Risk Assessment and Management*, 49–79. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119317906.ch3.

Funtowicz, Silvio O., and Jerome R. Ravetz. 1990. *Uncertainty and Quality in Science for Policy*. Springer Science & Business Media.

Helton, Jon C., and David E. Burmaster. 1996. ‘Guest Editorial: Treatment of Aleatory and Epistemic Uncertainty in Performance Assessments for Complex Systems’. *Reliability Engineering & System Safety* 54 (2): 91–94. https://doi.org/10.1016/S0951-8320(96)00066-X.

Jones, Roger N. 2001. ‘An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessments’. *Natural Hazards* 23 (2): 197–230. https://doi.org/10.1023/A:1011148019213.

Lemos, Noah. 2007. *An Introduction to the Theory of Knowledge*. Cambridge University Press.

Morgan, Kara. 2005. ‘Development of a Preliminary Framework for Informing the Risk Analysis and Risk Management of Nanoparticles’. *Risk Analysis* 25 (6): 1621–35. https://doi.org/10.1111/j.1539-6924.2005.00681.x.

O’Brien, Niall J., and Enda J. Cummins. 2011. ‘A Risk Assessment Framework for Assessing Metallic Nanomaterials of Environmental Concern: Aquatic Exposure and Behavior’. *Risk Analysis* 31 (5): 706–26. https://doi.org/10.1111/j.1539-6924.2010.01540.x.

Power, Michael, and Lynn S. McCarty. 1998. ‘Peer Reviewed: A Comparative Analysis of Environmental Risk Assessment/Risk Management Frameworks’. *Environmental Science & Technology* 32 (9): 224A-231A. https://doi.org/10.1021/es983521j.

PSAN. 2010a. *Guidelines Regarding the Framework Regulations*. https://www.ptil.no/en/regulations/pdfs-of-regulations.

———. 2010b. *Regulations Relating to Management and the Duty to Provide Information in the Petroleum Activities and at Certain Onshore Facilities (the Management Regulations)*. https://www.ptil.no/en/regulations/pdfs-of-regulations.

———. 2015. *Guidelines Regarding the Framework Regulations*. https://www.ptil.no/en/regulations/pdfs-of-regulations.

———. 2016. ‘Risikobegrepet i petroleumsvirksomheten [The risk term in the petroleum activities]’. Petroleum Safety Authority Norway. https://www.ptil.no/contentassets/1b253609b7b940069e0acd005861c7ca/risikorapport-2016-nett.pdf.

Refsgaard, Jens Christian, Jeroen P. van der Sluijs, Anker Lajer Højberg, and Peter A. Vanrolleghem. 2007. ‘Uncertainty in the Environmental Modelling Process – A Framework and Guidance’. *Environmental Modelling & Software* 22 (11): 1543–56. https://doi.org/10.1016/j.envsoft.2007.02.004.

SRA. 2018. ‘Society for Risk Analysis Glossary’. https://www.sra.org/sites/default/files/pdf/SRA%20Glossary%20-%20FINAL.pdf.

Tucker, W. Troy, and Scott Ferson. 2003. ‘Probability Bounds Analysis in Environmental Risk Assessment’.

Winkler, Robert L. 1996. ‘Uncertainty in Probabilistic Risk Assessment’. *Reliability Engineering & System Safety*, Treatment of Aleatory and Epistemic Uncertainty, 54 (2): 127–32. https://doi.org/10.1016/S0951-8320(96)00070-1.

List of figure and table captions

Figure 1. Main features of the risk-exposure model (Aven 2012b).

Table 1. Generic risk description components and specific examples relating to environmental risk assessment.

Table 2. Assumption settings; based on Berner & Flage (2016).

Table 3. Classification of assumptions. NA if a deviation is considered impossible.

Table 4. Assumption bias for assumptions associated with strong knowledge.

Table 5. Assumption bias for assumptions associated with moderate/weak knowledge.

Table 6. Comparison of risk sources, events/hazards, and consequences common as well as specific to the Arctic and the North Sea.