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Inadequate risk assessments – A study on worst-case scenarios related to petroleum exploitation in the Lofoten area[☆]

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ABSTRACT

Heated debates are currently taking place on whether to open the area of Lofoten and Vesterålen in Northern Norway for petroleum production. Seismic explorations in this area have indicated promising petroleum resources. The area is known for its unique landscape and as a key spawning and nursery area for several economically important fish species. It hosts significant bird colonies and the world's largest-known deep-sea coral reef. New areas will be opened to petroleum production only if its high environmental value can be maintained. A risk analysis approach has become central to this decision, where the probability of a 'worst-case scenario' (a major oil spill) is assessed together with associated environmental impacts. This paper examines and characterises uncertainties associated with these risk assessments and some of the surrounding debates. Further, the paper reveals implications of these uncertainties: (1) potential values embedded in the risk assessments, (2) lack of validity of quantified worst-case scenarios and their probabilities and impacts, (3) limited prospects of filling addressed knowledge gaps and (4) how risk assessments restrict the debate on what issues and uncertainties are considered relevant. Taken together, this suggests that discussions on alternative approaches to decision making should be more prominent in public and political debates.

1. Introduction

The question of opening Norway's northern offshore areas for petroleum production has been a long and heated political debate. The values at stake are considerable. On one hand, petroleum production promises to underpin Norway's economic wealth and people's standard of living, both locally and nationally. On the other hand, petroleum production, and in particular a major oil spill in the area off the Lofoten and Vesterålen islands and Senja (from now on referred to as the 'Lofoten area'), is feared to have the potential to significantly disturb and alter vulnerable ecosystems and thereby damage fisheries and tourism in the area.

Large areas in Norwegian waters have been opened to petroleum exploitation since the first oil field was discovered in 1971. Some areas still remain closed, as the northernmost area of the Barents Sea and the Lofoten area. The closure of these areas was a result of political processes where the importance of ecological factors such as biodiversity and biological production played a central role. The Lofoten area holds some of the worlds' largest fish stocks [1] and bird colonies [2,3].

To 'open' an area means that the area is earmarked for potential oil exploitation and that petroleum companies can apply for production licenses. Before an area is opened, an impact assessment of the petroleum activities is required, including risks of pollution [4]. One of the standard elements of such risk assessments is to define a 'worst-case scenario', which is a major blowout with a specific duration, rate, oil type, location and probability, supplemented by an assessment of the associated environmental impacts. The quality and legitimacy of the produced worst-case scenarios are at the centre of political debates, reflected in newspaper headlines. In "Misleading picture of risks" [5] the Ministry of Environment criticises the petroleum sector's chosen sites for assessing potential blowouts, claiming that these sites are further away from the shore than the promising petroleum fields. The article "Refuses catastrophe scenario" [6] exposes a disagreement between petroleum authorities and environmental and fisheries' authorities on the relevance of simulating the effect of a Deepwater Horizon sized oil spill in the Lofoten area, an oil spill three times the size of the established worst-case scenario.

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The impact assessments of a worst-case scenario have also shown to be controversial. In the article “Accused of sabotaging the oil debate” [7], marine scientists are accused of taking a political position when advising against opening the Lofoten area to petroleum production, since scientific evidence suggests that the potential harm is insignificant. Also, a marine scientist is pilloried for stating that the probability of destroying a whole yearclass of cod larvae in case of a major oil spill lies between 0 and 100% [7]. In addition, the scientists were criticised for applying safety factors to each component when quantifying impacts instead of applying this to the final outcome, arguing that the risks become highly exaggerated [7].

Also in the academic literature, different views are expressed on the production of knowledge related to this policy issue. Hjermann et al. [8] point to specific knowledge gaps that need to be filled concerning the impact of an oil spill on environmental and ecological processes. Still, they argue that stochastic processes make the predictions of long-term effects impossible to achieve. Knol [9] acknowledges that there is a substantial uncertainty, but questions the usefulness of ‘filling knowledge gaps' because it is unclear how filling such gaps will support decision-making. She further argues that natural science has dominated the process on assessing risks and that the process would have benefitted from rather being attentive to social issues and concerns [9].

It has long been argued that policy problems characterised by high stakes, uncertain facts and conflicting values, need to place uncertainty in science at the centre of the debates (see for example [10–15]). Uncertainty makes different interpretations possible, and values may be embedded in the knowledge production. The choice of scope of an investigation, the choice of method and presentation of results can favour one policy outcome over another.

The aim of this paper is to examine key uncertainties associated with defining the risk assessment of a worst-case scenario for the Lofoten area and to discuss how they affect the relevance of such assessments. It starts by presenting some historical background on the development of worst-case scenarios for petroleum production in Norwegian waters together with management policies to help us understand the situation on risk assessments today. The paper then seeks to characterise main uncertainties related to the worst-case scenario in the Lofoten area concerning: (i) the estimated probability and characteristics of a worst-case scenario and (ii) the modelled impacts of such an oil spill. In parallel, the paper shows how uncertainty has allowed different interpretations of ‘facts’ among experts. Uncertainties are further discussed whether they can be reduced and/or resolved, and whether values are embedded in the knowledge production. In light of the discussed uncertainties and the narrow scope of discussed environmental impacts of a blowout, the paper finally questions the relevance and role of risk assessments based on the worst-case scenarios: what kind of public debate and decision-making are they able to support?

2. Background

2.1. Opening areas in the north

The search for petroleum on the Norwegian continental shelf started in the 1960s. Exploration was only allowed south of the 62°N due to unsettled border issues. Environmental concerns and consequences for the fisheries were not central political topics until the 1970s. When the government in 1974 started the discussion on opening areas in the north, it was recommended that this would require concern for the environment and existing enterprise [16]. From that time on, there has been disagreement on whether to open which areas, based on the different perceptions on whether the implied risks were acceptable or not. In 1988, a large part of the Barents Sea was opened [17], while areas south of Lofoten were opened in 1994 [18]. The Lofoten area, Nordland VII and Troms II (see Fig. 1), remained closed and still are. Nordland VI (a part of the Lofoten area) was closed again in 2001, when the preparation for the Management plan for the Barents Sea and the Lofoten area (from now on referred to as the ‘Management plan’) was initiated [19].

2.2. The development of risk assessments

A blow-out on the Bravo platform in the North Sea in 1977 put worst-case scenarios at the forefront of the debate, with a particular focus on the probability of a blowout. Impact assessments and estimated probability of accidents became mandatory for the petroleum industry in the Pollution Control Act of 1981 [20]. The act articulates that potential polluters need to undertake an impact assessment of realistic accidents and estimate the probability of these. Impact assessments of petroleum activities in a broader sense were made mandatory through the Petroleum Act of 1985 [21].

As a consequence of the Alexander Kielland accident in 1980, the petroleum authorities required that risk assessments had to include risks with a probability larger than once every 10,000 years [22]. This criterion was abandoned in 1990 [23,24]. Instead, the industry was given the responsibility to minimise any risk by addressing potential risks, assessing them and specifying acceptance criteria [23].

Models for assessing worst-case scenarios were developed and used routinely by the industry. Their purpose was to improve oil well dimensions and oil spill protection systems. The more recent model versions consider how a set of possible future oil spills may disperse (by simulating currents, winds, petroleum composition, volume of spill, etc.), together with their possible environmental impact (toxicity of oil, overlap with fish eggs and larvae, seabirds, type of seashore it could hit) [25].

2.3. Cross-sectoral cooperation leading to shared responsibilities

The Norwegian government decided in 2001 to develop an integrated ecosystem-based Management plan for the Barents Sea and the Lofoten area [26]. Environmental impact assessment and assessments of socioeconomic impacts were developed for all sectors of human use. The resulting Management plan aims to balance industry interests with environmental sustainability [19]. It was ratified in 2006 and updated in 2011, where part of these processes required public hearings. Three cross-sectoral forums were appointed to annually update status reports for the Management plan: the Management Forum for the Barents Sea–Lofoten Area, the Advisory Group on Monitoring, and the Forum on Environmental Risk Management. The members of the latter include state research institutes and directorates, representing various disciplines and industry sectors related to the Barents Sea and Lofoten area. Their mandate has been to work with risk issues associated with acute pollution in the Management plan area [27]. For example, as a consequence of the Deepwater Horizon blowout in the Gulf of Mexico in 2010, the forum was asked to evaluate the relevance of this blowout to the knowledge basis for establishing the worst-case scenario for the Lofoten area [28].

The cross-sectoral forums constitute arenas for discussing claims and methodological approaches that previously belonged within the domain of a single sector. For instance risk assessments were previously the responsibility of the petroleum sector. The development of research projects has been another arena for contact between sectors. The Research Council of Norway has financed

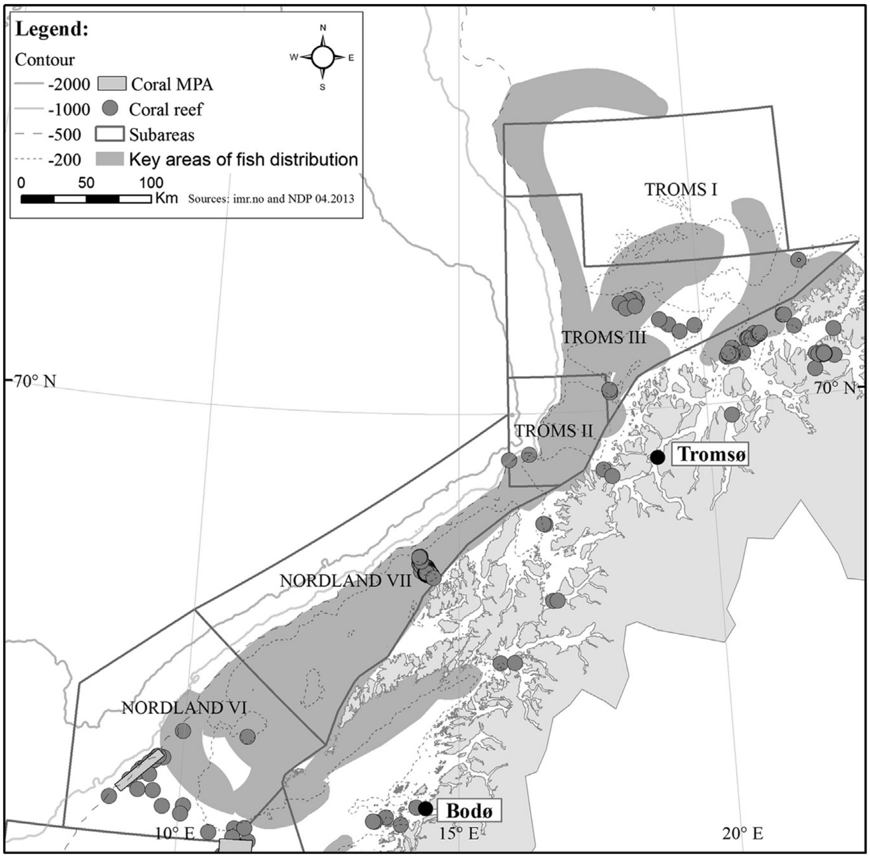

Fig. 1. The Lofoten area and adjacent waters. Troms II, Nordland VII and Nordland VI are closed to petroleum production. These areas include coral reefs and are spawning and nursery areas for several fish stocks. The marine protected area (MPA) is closed to bottom trawling.

several projects on impacts of oil spills and produced water [29]. Some of these projects, and the others financed directly by oil companies, have focused on the refinement of impact assessments related to worst-case scenarios. Although cross-sector involvement increases mutual understanding, it has also led to some heated debates, as the above-cited newspaper headlines suggest. This paper presents some of these debates.

3. Uncertainties and disagreements

This section presents key sources of uncertainty related to worst-case scenarios, their estimated probabilities and associated impacts concerning the Lofoten area. It further shows how these uncertainties allow different interpretations and can result in disagreements. Both the subsections conclude with a discussion on whether the uncertainty is reducible and controllable through quantification.

3.1. Worst-case scenarios and their probabilities

The updated Management plan presents nine oil spill scenarios with variations concerning spill size, petroleum composites, type of events, release sites and environmental impacts [30]. The worst-case scenario is defined to be 4500 t of oil being released daily for 50 days and for seven different release sites [30]. The expected frequency of oil spills larger than 100,000 t is estimated for different production stages and different types of installations, varying between once every 15,576 and 62,500 years for each well [30]. Simulations of resulting oil slick distributions are not yet settled.

When establishing worst-case scenarios, the size of realistic blowouts and oil spills, their probabilities and the petroleum composite are estimated. The required industry standard expects blowout risk studies to reflect reservoir conditions, operational procedures, equipment to be used and weather conditions at the site of concern [31,25].

The estimates of relative frequencies are based on the data since 1988 from a database of global petroleum activity and incidents [30,32]. The blowouts in the Gulf of Mexico have not been considered relevant since the ratio of blowouts to number of wells has been higher than in the North Sea with statistical significance [28,30]. Due to strict procedure and technical requirements in the offshore sector in Norway, only one blowout was considered sufficiently relevant for Nordland VI (see Fig. 1): the blowout in UK waters in 1989 [33]. The relative frequencies used for risk analyses for drilling in Nordland VI are established on this single blowout relative to the number of drilled wells with no blowouts in the North Sea since 1988 [33]. This baseline estimate is 5.5 blowouts every 10,000 years [33]. Since there has been a technical and procedural development since then, resulting in a reduction of near misses that could have led to blowouts if the security barriers had failed, the baseline estimate is reduced to 1.5 every 10,000 years [33,28].

The procedure for deciding the baseline estimates for the other subareas of the Lofoten area have been challenging to find. Reports refer to the same database and software as used for Nordland VI, but do not include information on the number of blowouts and non-blowouts. It is reasonable to assume that judgments on what constitutes comparable conditions have been similar.

Global experience suggests that the probability of a blowout varies with production stage, choice of technology and geological conditions, and the relative occurrences between such conditions are estimated. The resulting factors are applied to the baseline estimate producing relative frequencies for different conditions and for different blowout releases [28,33–37].

The worst-case scenarios and petroleum composites are estimated in a similar way and from the same database. Flow rates are determined from documented blowout flow rates, where physical and geological conditions are comparable. For example, reservoir pressure is a key factor [28]. The drift of an oil slick is estimated using a simulation model taking into account the blowout site, oceanographic features and oil properties [28].

3.1.1. Sources of uncertainty

As stated in the Management plan, historical data are representative for the future only to a limited degree [30]. There are several factors that contribute to uncertainty in assessing the probability of a blowout: (i) *representativeness of empirical data* – workplace conditions, political, geological and environmental conditions will never be identical to any other situation, (ii) *effects of innovations* – the technical developments and improvements of routines are challenging to account for. Not all are considered sufficiently determined to be included in the calculations [33,34], (iii) *surprises* – whether future developments will introduce new and unexpected events are not possible to know, and (iv) *data scarcity* – one blowout limits the confidence in the probability estimates.

The above uncertainties are also relevant in determining an appropriate size of a worst-case scenario oil spill, which again influences its dispersion. The sites, ocean currents and weather conditions determine the dispersal of oil slicks, as for example how much of an oil slick will hit the coastline and whether it will be dispersed or biodegradated. Production sites at the continental slope are associated with higher probabilities of a blowout due to higher pressures, but the resulting oil slick will probably be transported farther away from the coastline and the critical distribution areas of fish. Sources of uncertainties include (i) *the sites* – the Lofoten area is not sufficiently explored for locating optimal production sites, (ii) *ocean currents* – the grid resolution of the ocean models providing ocean currents and hydrography is coarse [27], (iii) weather conditions are complex and indeterminate and (iv) *the partly unknown petroleum composite*, which influences an oil slick's fate in the ocean. All these factors contribute to uncertainty in simulated oil slick dispersal, which again are used to assess impacts of a worst-case scenario.

3.1.2. Discussions and disagreements on factors defining worst-case scenario

As mentioned above, the Forum on Environmental Risk Management was requested to evaluate whether the current worst-case scenario needed to be revised [28]. This generated discussions across sectors on what constitutes *comparable* conditions, and on the effect of necessary expert judgments (due to uncertainties listed in the above subsection). The principal conclusion in the report states that the conditions in the Gulf of Mexico are not representative for the Lofoten case, and therefore, the size of the worst-case oil spill should remain the same. However, a minority of the Forum, with members representing the environmental and fisheries sectors, requested simulations of oil spills with a higher spill rate and longer duration [28].

Simulations of resulting oil slick distributions have not yet been made, and there is still disagreement concerning scenario design and accuracy of models involved (both the oil dispersal and fate models and ocean models) [38]. Also criteria for selecting information for the impact assessments are not yet settled [30].

3.1.3. Characteristics of the addressed uncertainties

A reduction of the uncertainty associated with the probability of a worst-case scenario in the Lofoten area is not likely to be achievable, as it will require more experience with blowouts and control of all external factors, and their interactions, that contribute to a blowout. The experts in charge consider the data too poor for estimating confidence intervals for the release rate and the duration [28]. With this in mind, the relevance of estimated probabilities should be questioned. Funtowicz and Ravetz [10] call science where uncertainty in the input data is suppressed to avoid indeterminate output as ‘pseudo-science’. This produces meaningless numbers in the sense that it is unknown whether the number is correct or far off [10]. Substantial uncertainty necessitates assumptions to be made in order to produce quantities. The assumptions affect the resulting numbers and may benefit a certain political decision, for example whether a risk is perceived as acceptable or not [39]. It is noteworthy that experts emphasise that the difference between blowout frequencies in the Gulf of Mexico and Norwegian waters is significant, while confidence intervals around blowout related measures are considered unachievable because of uncertainty [28]. The implied uncertainty stands in stark contrast to the precision in the presented frequency numbers in the Management plan, where the uncertainty clearly lies in the first digit of for example *once per 15,576 years* [30].

Some of the other uncertainties listed in the previous section may be possible to reduce. For example, simulating oil releases from added sites can enrich our perception of the extent of polluted areas. However, uncertainty can be reduced only to a limited extent. Personal judgment and expert opinion will necessarily be a part of such risk assessments because they handle rare events in complex systems [40].

3.2. Impacts of worst-case scenarios

Simulation models for worst-case scenarios have been compared to fish larvae distributions since 1980 [41]. Only the most economically important fish stocks were considered. In the Lofoten area this is Northeast Arctic cod, the world's most abundant cod stock [7]. The stock migrates from the Barents Sea to the Lofoten area to spawn [1]. Eggs and larvae drift with the coastal currents towards the Barents Sea, passing the narrow continental shelf where the promising petroleum fields are located [1]. The second fish stock of concern is Norwegian Spring Spawning herring, one of the largest fish stocks in the world. Herring spawn along the coast with the main spawning area off Møre, but the herring larvae must pass the same promising petroleum area on their way north to their nursery grounds in the Barents Sea [1].

A major oil spill in the Lofoten area during the spawning season can affect eggs, larvae and the spawning behaviour of mature fish. If possible, bigger fish can escape a polluted area, but eggs and fish larvae are far less mobile [8]. With mature cod spawning in a concentrated area, a major oil spill could more easily overlap the whole distribution area of the resulting larvae [8] and possibly affect an entire yearclass of cod.

Simulations of oil dispersal and the probability of various levels of population loss for several species of marine birds and mammals are presented in the Management plan, while improvements are requested on the consequences for fish species [8,28]. The current improvements include coupling an oil dispersal model and a distribution model for Northeast Arctic cod eggs and larvae [42]. The simulated diurnal migration of larvae and the refined modelling of vertical location of fish eggs are expected to improve the estimated exposure of larvae and eggs to toxic oil components [42]. Also, there are efforts to simulate the effects of egg and larvae mortality on the future cod stock [43]. These projects are financed by the Research Council of Norway and the petroleum sector [29,42,43].

3.2.1. *Sources of uncertainty*

In spite of expected improvements, uncertainty will remain. The simulated overlap between oil spill and mature cod, eggs and larvae is still uncertain. How much will the, partly unknown, diurnal pattern of larvae, moving up and down the water column, increase or decrease their chances of getting affected by an oil slick? How does cod in early life stages follow ocean currents? To what extent can mature cod avoid an oil slick? Species such as cod, and especially herring, have variable recruitment success between years. Typically a few good yearclasses dominate the population, whereas most years produce only a moderate level of recruitment. This variability increases the potential harm that a spill in a single year can inflict on the stock [8]. And although spawning fish may avoid an oil spill, they may choose less favourable spawning locations or the spawning ritual may be affected. It is also an open question whether the majority of the successful recruits come from only a few portions (limited in space and time) of the spawned eggs or whether there is a relatively homogenous contribution from different spawning sites and times [8]. An entire yearclass could potentially be killed although only a part of the spawning stock is affected. Further, the abundance of a stock and its distribution prior to a major oil spill will influence the impact of a major oil spill, but the abundance fluctuates significantly from one year to another, resulting in uncertain assessments and predictions, even before taking effects from an oil spill into account.

There is still uncertainty associated with which concentration levels of oil are lethal for fish at various stages. The intensive research following the Exxon Valdez oil spill in Alaska, 1989, identified eggs and fish larvae to be the most sensitive life stages for oil pollution. The lethal dose of oil pollution was suggested to be considerably lower than the previous research indicated [44,45]. In the US, there has been an ongoing discussion and disagreement between government scientists and Exxon employed scientists about the sensitivity of fish eggs to oil pollution [46]. This issue has also been a part of the discussion in Norway, and the updated Management plan settled on a toxicity threshold based on an average from a review of the academic literature [47]. Several reports discuss situations where there may be exceptionally high toxicity. Some substances are more toxic when exposed to light, making fish that spawn close to the surface more vulnerable [48]. Some species (for instance herring) may be more exposed to oil spills because they depend on going to the surface to fill their swim-bladder and thereby get exposed to oil [49].

Adding to the complexity of the issue, fish larvae depend on a continuous availability of prey in order to survive. In case of a major oil spill, some plankton will die and some plankton will consume oil, but survive. The survival of larvae will thus hinge on the recovery time of plankton and/or whether consuming petroleum-affected plankton will kill larvae. These interactions will probably only partly be taken into account because of the complexity of the problem and lack of knowledge and data.

As a final remark, an ideal assessment of environmental impacts would include the effects on every single species in the area, every stage of their life cycle, cascading effects on ecosystem components, all possible impacts on the environment, and both the short- and long-term effects [8]. This means that there is considerable uncertainty related to impact assessments.

3.2.2. *Discussions and disagreements on impacts of a worst-case scenario*

There have been mainly two discussions concerning impact assessments: the lack of details in impact assessments and the presentation of assessment results. The recent and the ongoing projects on impact assessments can be understood as critique of the simplistic versions developed on contract from the petroleum sector. Considerable effort has been put into refinements of these assessments.

The starting point of impact assessments is a range of spill sizes (varying duration and rate) from numerous locations (both geographically and at different depths in the water column), and the assessments include cod and herring. The produced results are numerous, and there is an ongoing discussion on whether to focus the results on (1) *the expected outcome*, predicting the average adverse effects of an oil spill on fish stocks, or (2) *the worst-case effects* of the worst-case scenario, showing the likelihood of serious adverse effects, as for example, the loss of more than 50% of a yearclass. The spill scenarios developed for the revision of the Management plan [27] predicted that on average even the worst-case scenario would have little adverse effects, but that there was a certain probability it could affect a large proportion of the yearclass of cod and especially herring. These effects would be further magnified if that occurred during a year with high recruitment, further diverging the *worst possible* outcome from the *expected* one.

3.2.3. *Characteristics of the addressed uncertainties*

The experience from the 1989 Exxon Valdez oil spill in the Gulf of Alaska shows that long term effects are not only difficult to predict, but also challenging to determine even with the benefit of hindsight [50]. Before this oil spill, it was assumed that acute mortality was the key concern, but experience from this oil spill indicates an unexpected long-term effect on wildlife [51]. On the other hand, uncertainty still remains on whether the oil spill was the major cause of the herring stock collapses [49].

Present efforts of refining risk assessments have the potential to reduce some of the associated uncertainties. For example, including cod larvae's diurnal migration pattern may offer new insight in potential overlaps between an oil slick and cod larvae. However, including more detailed information will introduce new layers of uncertainty: Is the model resolution sufficiently fine to assess the exposure of larvae during their migration up and down the water column? What other factors determine survival of larvae to later life stages?

There are several sources of uncertainty that make the associated uncertainty challenging to reduce: (i) Major oil spills are rare, and hence empirical knowledge is scarce. The conditions have rarely been the same from one blowout to another, and oil tanker accidents and recent blowouts reveal unpredicted dispersal or phenomena that have not been observed before, for example the fate of an oil slick [52,53]. (ii) Ocean currents and other environmental conditions are influenced by stochastic processes and will affect the distribution of an oil slick, on fish stocks and other marine life in a non-predictive way [8]. (iii) Political, cultural, natural and technical conditions change and will always be unpredictable to some extent. Taken together, uncertainty will necessarily remain, both on the probability and the size of a worst-case scenario. The uncertainty is thus reducible only to some indeterminate extent.

Concerning the presentation of risks, there is a structural issue on how the “worst case” is defined. The “worst case” could be related only to the size of the oil spill, but it could also be defined as the worst case in terms of fate, weather conditions, time of year, overlap with fish larvae, etc. As a result, the risk assessment for an equally large oil spill is driven by the choice of how that “worst case” is defined. A second issue relates to the low probability, high impact and nature of the risk. Presenting only the worst outcome would overemphasise the potential danger, whereas presenting averages tends to produce an overly reassuring outcome by diverting attention away from the rare, severe, accidents. Finally the temporal and spatial scales are a matter of choice, for example weighing the local environment against the risks to the large fish stocks. The above aspects illustrate that impact assessments are based on a range of choices that can generate quite different answers.

4. Discussion on uncertainty

The previous section pointed to a number of uncertainties related to risk assessments, and the paper has shown that uncertainties have given rise to disagreements between experts. This section will now discuss the addressed uncertainties in terms of their possible consequences: will the uncertainty issues be resolved? And given the narrow scope of the risk assessments, for what purposes are they relevant? The section then discusses the various roles of risk assessments and the associated uncertainties.

4.1. Controlling uncertainty

A relevant concern is whether the above described uncertainty can be described through quantitative measures. To some degree it can: quantitative uncertainty measures can be provided in cases where uncertainty is due to the lack of measurement precision and to some extent variability. But uncertainty cannot fully be quantified when facing ignorance – what we do not know, and even further: what is beyond our conception of what is possible [10]. There are aspects of future natural, political, cultural, and technical conditions that cannot be anticipated, and that most likely would affect not only the numerical value of the estimated worst-case scenario, but also our understanding of it, if there were more knowledge. Likewise, there are ecosystem processes that are not understood, and it is unknown how or whether these affect larvae and the future fish stocks. This implies that risk assessments are associated with uncertainty that cannot be quantified adequately. The problem is that it is not possible to know whether this uncertainty is negligible or whether it decreases the relevance of the risk assessments for decision making.

Yet, the implied ignorance just described might be negligible compared to the uncertainty resulting from the narrow scope of risk assessments or from disregarding other possible risks than major oil spills. First, the public debates and the debates between experts have concentrated on the probability of a major oil spill, which reflects just an interval of a continuous event space of oil spill sizes, where a possible oil spill could be smaller and still have a significant impact on the environment. Second, the scope of impacts of a major oil spill is concentrated on effects on cod and herring larvae, while impacts on other species are not considered. Third, most long-term effects and cascading effects on ecosystem components are not addressed. And fourth, whether a major oil spill can have an irreversible effect on a fish stock or an ecosystem is not a part of the public or expert debate. A consequence of the choice of scope and models is that possible impacts are reduced to a temporary impact because the choice of scientific approach includes an assumption that the cod stock will, given time, recover from an oil spill. But experience, for example on the overfishing of Northern cod [54] or the effects of the Exxon Valdez oil spill [51], suggests that major impacts can cause changes in the ecosystem structure which make it difficult, maybe impossible, for stocks or ecosystems to recover.

Weinberg [55, p. 209] introduced the concept of 'trans-science', defined as "questions that can be asked of science and yet *which cannot be answered by science*". Risk assessment is in the realm of trans-science: first, a sound empiric basis for calculating a worst-case scenario and its probability would have required decades, at least, to provide a sufficient number of comparable blowouts and second, due to the complexity of ecosystems, a complete assessment of impacts is not achievable. This means that choices, of which some will not be science based, need to be made on how to approach the problem of whether petroleum production in the Lofoten area constitutes an acceptable risk to the environment, and if so, in which localities and with what safeguards.

4.2. Relevance of risk assessments

A pressing question is whether the present choice of approach, resulting in a quite narrow scope of risk assessments, is relevant for policy making. As argued above, quantified measures for risk assessments and its associated uncertainties are impossible to achieve without, perhaps considerable, uncertainty. Still, risk assessments may indicate important perspectives on risks. It is reasonable to assume that in case the area is opened, simulation studies may indicate sites that are likely to cause less harm than others in case of a major oil spill. The oil industry has proven to hold technological equipment and knowhow to drill horizontally for quite some distance and has used this technology to avoid drilling close to vulnerable benthic communities such as coral reefs [56]. A different aspect of developing risk assessments is that the cooperation between sectors on developing criteria for these has already facilitated new discussions and reflections on knowledge and uncertainty.

Taken together, the development of risk assessments based on the worst-case scenarios has a certain potential. However, it is disputable whether worst-case scenarios can be used as a key instrument for deciding whether to open the Lofoten area or not. How well do effects on cod larvae represent the effects on the ecosystem? And how can the attention these risk assessments get from the experts and the public be understood?

4.3. Risk assessments and their framing

There is a need to look closer at the role of risk assessments and their uncertainties. First of all it must be clear what it is. A worst-case scenario is not a worst imaginable scenario. It is not a combination of events, for example a major blowout together with some other kind of accident in the area, amplifying unfortunate impacts. It is not an imagined terror attack on installations, and the impact of a blowout is not combined with other human stressors (overfishing, aqua-culture, discharges from other industries and ocean traffic). As defined, a worst-case scenario is a scenario based on the so-called "realistic" major oil spills caused by a blowout. Because its scope of impacts is narrow and other risks are not included, it is a rather incomplete risk assessment.

To understand the roles of worst-case scenarios and risk assessments, two perspectives need to be examined. From a petroleum company's point of view, a risk assessment is a tool for internal management. The company has to fulfil certain criteria according to the regulations and laws in order to get permission for petroleum production. Also, risk assessments are needed to take action and for cost-benefit considerations, as blowouts are very expensive for an oil company. From a political point of view, risk assessments serve as a tool to decide whether the risk is acceptable to society, and the public's concerns on possible impacts may be very different from a petroleum company's concern. These two different, and to some extent conflicting, uses of risk assessments raise questions about the design and ownership of the risk assessment process. Risk assessments may serve their purpose for internal management and may not be controversial within the sector. Now these risk assessments are brought into cross-sectoral forums and are in addition being applied for an area associated with rich fauna, great fisheries values and strong identity sentiments. For the fisheries and environmental sector, worst-case scenarios have defined an arena to highlight the importance of environmental values, quality knowledge and the need for research [9]. Thereby, risk assessments and the associated uncertainties provide opportunities to postpone decisions. Taken together, risk assessments and worst-case scenarios serve as a common device for discussion and negotiation while their meaning and function varies.

This paper has pointed to the limited scope of risk assessments and has questioned their relevance. Yet, discussions on their quality centre less on their scope and more on their details, accepting the narrow framing of the problem. Criticisms include the criteria for defining the worst-case scenario, the choice which ecosystem impacts to examine, the lack of realism in quantifying larvae mortality and its resulting effect on the future fish stocks, and the communication of results to policy makers and the public. These demand refinements of the existing approach, and a range of efforts, including research projects, are attempting to meet these demands. This implies that the criticism centres on the quality of the existing risk assessment based on the worst-case scenarios, rather than discussing whether these are informative or can be used for deciding whether the environmental risks are acceptable.

The following may partly explain this situation. Risk assessments were initially developed by the petroleum sector and were used by the same sector to make decisions. Through the process linked to the Management plan, other sectors were invited into a settled culture for assessing risk. However, it should be pointed out that the way knowledge gaps are addressed in the preparatory report for the first Management plan [19] matches the approach to refine the impact assessments. The report gives the impression that the listed knowledge gaps are possible to fill, that at least some should be filled and that filling knowledge gaps will increase the quality of advice to decision making [9]. The recent and present efforts to refine impact assessments correspond to several of the listed knowledge gaps. The particular framing of the risk assessment decides which uncertainties are relevant to discuss and which are not. In this case, refinements of worst-case scenarios and risk assessments are legitimate while questioning the narrow scope is less so. A worst-case scenario can therefore be understood as a certain way of packaging uncertainty in the policy debate. A consequence of this framing is that representatives from the petroleum sector emphasise the low probability (e.g. in [57]), while environmental NGOs emphasise the great impacts of a major oil spill (e.g. in [58]).

4.4. Uncertainty and values

The discussions on uncertainties in this paper suggest that value-laden choices are made (consciously or unconsciously) at three stages: when deciding the scope of risk assessments, when methodological choices are made, and when deciding how results should be presented. It is possible that the policy debate would have been different if other environmental impacts had been emphasised (smaller oil spills, irreducible changes, etc.), if qualitative approaches were more central or if the presentation of risks had been different. Such choices may favour one political action over another. The same issues arise with various handlings of uncertainty. All these choices are value-laden because they have the potential to influence perceptions on what is at risk, how high the risk is, and what ought to be done with regard to the issue.

The substantial uncertainties addressed in this paper suggest that the final decision is more a value question than a scientific question. In this case a ranking of risks could be performed to ensure a wider scope on the issue. Risk issues include smaller sized oil releases, loss of work places, population decline in the Lofoten area, decline of economic wealth and standard of living in Norway, the loss of industry know-how, pollution from everyday operations, Norwegian identities at stake, collapsed ecosystem, the petroleum industry's contribution to the acidification of the oceans, political goals on reducing CO_2 emissions, the national economic dominance of the petroleum industry and how this affects the conditions for other industries in Norway in times of global economic crises, future instability of petroleum income shares in a global market and others. These risk issues may be just as relevant to look into as risks addressed by worst-case scenarios.

In light of the addressed uncertainties, limitations and value-ladenness, to what extent is there a role for experts and science? Knowledge about technical and environmental conditions is clearly essential for decision making. However, since values are often embedded in methodological choices, uncertainty needs to be carefully addressed [10]. This paper seeks to contribute to an increased awareness around crucial uncertainties and their roles. Because of value-ladenness and uncertainty, extended peer-review is central in post-normal science [11]. Our findings suggest that the policy process and the role of experts and science should be discussed and revised in relation to open the Lofoten area to petroleum production. However, further discussions on this topic lie outside the scope of this paper.

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