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# An environmental risk assessment framework for enhanced oil recovery solutions from offshore oil and gas industry

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ABSTRACT

Environmental risk assessments are necessary to understand the risk associated with enhanced oil recovery (EOR) solutions and to provide decision support for choosing the best technology and implementing risk-reducing measures. This study presents a review of potentially relevant environmental/ecological risk assessment (ERA) guidelines and, based on this review, proposes an initial suggestion of an ERA framework for understanding the environmental impacts from EOR solutions. We first shortlist the important elements necessary for conducting an ERA of EOR solutions from the selected guidelines. These elements are then used to build the suggested ERA framework for produced water discharges, drilling discharges and emissions to air from EOR solutions, which is the primary objective of the present study. Furthermore, the emphasis is placed on identifying the knowledge gaps that exist for conducting ERA of EOR processes. In order to link the framework with the current best environmental practices, a review of environmental policies applicable to the marine environment around the European Union (EU) was conducted. Finally, some major challenges in the application of ERA methods for novel EOR technologies, i.e. uncertainties in the ERA due to lack of data and aggregation of risk from different environmental impacts, are discussed in detail. The frameworks suggested in this study should be possible to use by relevant stakeholders to assess environmental risk from enhanced oil recovery solutions.

## 1. Introduction

In 2018, the International Energy Agency (IEA) presented the World Energy Outlook (WEO), which predicts an increase in energy demand of around 25% by 2040, in order to meet the requirements of an increasing population. Fossil fuels – particularly oil and gas – will continue to account for the majority of the supply to meet this increase in energy demand. "*Natural gas and oil continue to meet a major share of global energy demand in 2040, even in the sustainable development scenario. Not all sources of oil and gas are equal in their environmental impact*" ((International Energy Agency (IEA), 2018), p, 5). Currently, offshore oil and gas production accounts for around 30% of the world's energy production, and this share is expected to increase in the future (International Energy Agency (IEA), 2018; Zheng et al., 2016). Novel Improved Oil Recovery (IOR)/Enhanced Oil Recovery (EOR) technologies are currently being proposed as attractive solutions for increasing oil recovery efficiency from offshore oil and gas fields. However, these IOR/EOR solutions can have adverse environmental impacts, due to discharges to the marine environment and emissions to air.

Muggeridge et al. (Muggeridge et al., 2014) write that most oil companies are focusing on maximizing the recovery factor (RF) from currently operational fields, as it is becoming increasingly difficult to discover new oil and gas reserves. The average RF from oil fields is between 20% and 40% (Muggeridge et al., 2014). Enhanced Oil Recovery (EOR) methods involve the use of different technologies, such as water alternating gas (WAG) injection, smart water injection, and polymer flooding, to increase oil recovery from existing fields (Muggeridge et al., 2014; Torrijos et al., 2018). Improved Oil Recovery (IOR), a term used at times as equivalent to EOR, also implies improving oil recovery but, instead, by intelligent reservoir management and advanced reservoir monitoring techniques. By using a combination of IOR and EOR technologies, it is possible to increase the RF by somewhere in the range of 50% to 70% (Muggeridge et al., 2014).

Improving the RF is not only economically beneficial as it helps to

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maintain the production rate, but it may also be environmentally favorable when compared to setting up an oilfield in a newly discovered reserve. However, there can still be potential environmental impacts resulting from novel EOR solutions, due to produced water discharges, drilling discharges and emissions to air (Bakke et al., 2013; Sanni et al., 2017; Stephens et al., 1977; Zheng et al., 2016). Additionally, there can be environmental risk due to accidents. However, this study is mainly focused on the environmental risk related to the operational discharges from EOR processes. To avoid unwanted environmental consequences, we need to address three important questions: What are the specific environmental threats from EOR processes? Do we have a detailed ERA framework to assess environmental risk from EOR processes? Do we need new tools to assess the environmental impacts?

Let us consider an example of polymer flooding as a potential EOR process, to address the above-listed questions. Polymer flooding is usually carried out with anionic polyacrylamide (APAM) or partially hydrolyzed polyacrylamide (HPAM) (Brakstad et al., 2020). The recent study performed to assess the acute and sub-acute toxic effects on Atlantic cod from APAM polymers showed low or negligible toxic effects at concentrations lower than 150 mg/l (Hansen et al., 2019). However, the PAM polymers are persistent in the marine environment at higher molecular weights (El-Mamouni et al., 2002), and there is a lack of knowledge about the chronic toxic effects of these polymers. In order to have a solid ERA, it is important to understand the complete degradation pathway of PAM polymers and the associated toxicity of the degraded polymers. To understand this in further detail, there is a study ongoing on the depolymerization process of PAM polymers and the formation of their degradation products (Opsahl & Kommedal, 2021a,b), unpublished results). In addition, a cytotoxicity study using degraded PAM polymers on rainbow trout gill cells is being conducted (Opsahl & Kommedal, 2021c), unpublished results). Moreover, the monomer generated as a part of the degradation process is known to be toxic (Xiong et al., 2018). Despite the low or negligible acute toxic behavior of PAM polymers at a concentration of less than 150 mg/l, it is important to examine the environmental risk associated with the fate, possible accumulation over a long time and the degradation products of PAM polymers in the marine environment. Similarly, chemical compounds used as a part of an alkaline-surfactant-polymer (ASP) EOR process could also be a threat to the marine environment (Tackie-Otoo et al., 2020).

Another EOR process based on capture and injection of carbon dioxide ($CO_2$) offers a promising alternative for enhancing oil recovery and at the same time mitigating climate change by permanently sequestering $CO_2$. (Dai et al., 2014; Mac Dowell et al., 2017). Even though uncertainty in the oil prices make $CO_2$ – EOR less attractive, there are cases in which $CO_2$ – EOR could still be economically viable (Ampomah et al., 2017; Dai et al., 2016; Mac Dowell et al., 2017). A detailed study of both environmental and economic risk and benefits is therefore recommended before screening and implementing a particular EOR process for a given oil and gas reservoir.

More recently, the human induced seismicity due to anthropogenic activities has become a concern and may also pose significant environmental and economic risk. More than 100 instances of such seismic events are recorded due to conventional oil and gas operations and hydraulic fracturing (Foulger et al., 2018). Such seismic events during EOR processes may pose significant environmental and economic risk. However, the scope of current paper is to mainly consider the environmental risk from operational discharges or emissions occurring specifically related to the EOR processes or products (not related to possible accidental effects) and therefore risk due to induced seismicity is not discussed further.

To assess the environmental impacts, current ERA guidelines around the world can be an important reference point. ERA guidelines from different countries/regions present a generic ERA framework that can form a basis for conducting an ERA of EOR solutions. For EOR processes, the ERA framework from Smit et al. (2006a) (Environmental Risk Management System (ERMS) Report No. 3) presents a framework for drilling discharges. However, a holistic ERA framework for produced water discharges, drilling discharges and emissions to air from EOR solutions for offshore application is currently lacking. In the present study, we shortlist the important elements necessary for conducting an ERA from potentially relevant ERA guidelines around the world. These elements are then used to make an initial suggestion regarding an ERA framework for produced water discharges, drilling discharges and emissions to air from offshore EOR solutions, which is the main objective of the present study. Similar studies suggesting an ERA framework for different areas of application are available in the literature, for instance a framework from Skinner et al. (Skinner et al., 2016), which presents a detailed ERA framework based on an expert elicitation process. More specific ERA frameworks exist, for example from Landquist et al. (Landquist et al., 2013), presenting an ERA framework for polluting shipwrecks; from Lamorgese and Geneletti (Lamorgese & Geneletti, 2013), providing a framework for urban planning.

To understand current best environmental practices (BEP) and tools used for assessing environmental impact, a review of environmental policies applicable to the marine environment around the European Union is carried out. The guidelines from the Oslo and Paris Commission (OSPAR) are the most comprehensive in the context of ERA of EOR solutions. The model system Dynamic Risk and Effect Assessment Model (DREAM) is proposed as one of the suitable tools for an ERA of produced water and drilling discharges (Department of Energy and Climate Change, 2014). However, the applicability of the DREAM or similar model for the chemicals used in the EOR processes could be limited. In the case of the limited applicability of currently available simulation tools, there are opportunities to develop a novel tool for assessing the environmental impact from EOR processes. Finally, challenges involved in the application of the suggested ERA frameworks for novel EOR technologies are discussed. These challenges include uncertainty assessments and joint aggregation of risk from produced water discharges, drilling discharges and emissions to air. The uncertainties are mainly due to the lack of data regarding the use of polymers on a large scale and their degradation and toxic behavior in the marine environment.

The paper is organized as follows: ERA guidelines are reviewed, and the shortlisting of important elements necessary for conducting ERA is explained in Chapter 2. In Chapter 3, the ERA framework for produced water discharges, drilling discharges and emissions to air from EOR solutions is proposed. Also, a review of environmental policies for the marine environment around the EU is presented. In Chapter 4, there is a discussion about the ERA framework, knowledge gaps in conducting ERA and the challenges involved in the ERA of novel EOR solutions. Chapter 5 highlights the main conclusions.

## 2. Approaches for environmental risk assessment (ERA)

### 2.1. Scope of review

An ERA is a process of identifying and assessing the potential adverse effects on organisms, populations or communities mainly as a result of exposure to chemical and non-chemical stressors from industrial activities (Government of Canada, 2012; US Environmental Protection Agency (US-EPA), 1998). In this study, four guidelines for assessing risks to the environment are selected and reviewed. The criteria for selecting these guidelines are language, i.e. English, representation of the different geographical areas and relevance to the EOR context. The selected guidelines are generic and could form as a basis for ERA of any anthropogenic activity. The group of countries representing these guidelines contributes to around 30% of the world's oil and gas production (United States Energy Information Administration, 2019). All documents related to the guidelines, regulations and policies are collected through online resources. The selected guidelines in the present paper are assigned an identifying letter, to simplify subsequent comparison (Table 1). The research paper from Skinner et al. (Skinner

**Table 1**
Overview of selected Environmental Risk Assessment guidelines for review and comparison.

| Geographical region | Document reviewed | Comments | Identifying letter |
|---|---|---|---|
| United States of America (USA) | US EPA (US Environmental Protection Agency (US-EPA), 1998) | The methodology is broad in scope and includes three key phases: problem formulation, analysis and risk characterization. | A |
| Canada | Government of Canada (Government of Canada, 2012) | The methodology is for ecological risk assessment of contaminated sites in Canada. The framework includes four key phases: problem formulation, exposure assessment, effects assessment and risk characterization. | C |
| Europe | (European Chemical Agency (ECHA), 2016; European Chemical Agency (ECHA), 2008a; European Chemical Agency (ECHA), 2008b) & European Chemical Agency (ECHA), 2012 (R.6, R.10, R.16 & R.19) | The EU methodology is mainly intended for the assessment of chemicals and is focused on four key phases: hazard identification, exposure assessment, dose-response assessment and risk characterization. | E |
| United Kingdom (UK) | (Department of Environment, Food and Rural Affairs (DEFRA), 2011) | ERA framework in UK has four key phases: formulate problem, assess risk, appraise options, address risk. | U |
| Note: The article listed below is used as a reference for shortlisting important elements in the key phases of ERA. | | | |
| Not applicable | (Skinner et al., 2016) | The methodology from Skinner et al. is developed as a part of the expert elicitation process and consists of four key phases: hazard identification, exposure assessment, effects assessment, and risk characterization. | S |

et al., 2016) presents a generic ERA framework based on an expert elicitation process. The important components from this framework are shortlisted and used as a reference point for comparison among different guidelines. Since definitions of environmental and ecological risk assessment overlap to a large extent, ERA is used as an abbreviation for both environmental and ecological risk assessment.

### 2.2. Evaluation

To investigate the key elements in the selected ERA guidelines, the four key phases of the common ERA scheme are followed (Government of Canada, 2012; Skinner et al., 2016) (Fig. 1).

- Problem formulation: This is the first step in any ERA process where information about goals, hazard sources, contaminants of concern, assessment endpoint and methodology for characterizing exposure and effects is collected for an explicitly stated problem.
- Exposure Assessment: It is a process of measuring or estimating the exposure in terms of intensity, space and time in units that can be combined with effects assessment to characterize risk.
- Effects Assessment: The purpose of the effect's assessment is to characterize the adverse effects by a contaminant under an exposure condition to a receptor.
- Risk characterization: The process of estimating the magnitude of adverse ecological impacts based on the information collected from exposure and effects assessment.

In this study, important elements in these key phases are identified and compared with respect to the level of details covered about that particular element in the different guidelines (Table 1). A three-step scale is defined for this purpose, viz. *considered in substantial details, considered in limited details* and *not considered*. This exercise is useful in shortlisting important elements necessary for conducting an ERA and to refer such elements in a specific guideline for further information.

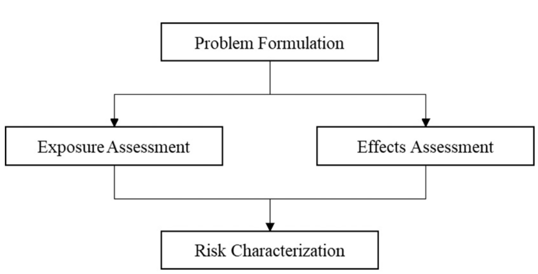


**Fig. 1.** Key phases in Ecological/Environmental Risk Assessment

### 2.3. Findings

Overall, no single guideline covers substantial details of all four phases in the ERA process. Most of the elements in the problem formulation and risk characterization are covered in substantial detail by guidelines A and C. All the guidelines have good theoretical coverage of exposure and effects assessment, and the guidance document on chemical safety assessment from the EU (E) prescribes specific equations to calculate exposure and no-effect concentration of chemical compounds in the receiving environmental media. (Table 2)

#### 2.3.1. Problem formulation

Problem formulation is a key phase of any ERA process, and two guidelines (A and C) dominate the details covered for all shortlisted elements in the problem formulation phase. On a broad level, the ERA process is driven by overall site management goals and regulations that set the expectations for the desired condition of the ecosystem and its components, in the context of future site use. In guidelines A and C, examples are explained to assist in framing management goals for any site, in conjunction with local/national/international regulations. The baseline site investigation carries considerable weight in any ERA process, as it gives information about current contaminant sources, distribution, transport pathways and ecological condition of the site, which is explained in detail by guideline C.

The contaminants of concern (COCs) are the compounds selected for evaluation in the ERA process, due to their inherent properties of causing damage to the ecosystem. Guideline C explains key points in understanding sources and the selection of COCs in detail. The sources of COCs that could be of interest include on-site point sources (e.g., historical spills), on-site non-point sources (e.g., contaminated groundwater), underground artificial conduits (e.g., sewers, pipelines), natural pathways (e.g., fractures in geological structures) and significant off-site sources. COCs are controlled by several factors affecting their fate and transport in the environmental media. Guidelines C, E, and S cover considerable details about the processes that control the fate and transport, viz. the physical (hydrolysis, photolysis, etc.), chemical (adsorption, volatilization, etc.), and biological (biodegradation, excretion etc.) characteristics of COCs, along with properties of the receiving environmental media (pH, air pressure, soil density, etc.).

The receptors of concern (ROCs) are any non-human individual species, population, community, etc. that is potentially at risk of exposure to a COC (Government of Canada, 2012). Detailed information about ROCs, such as identification of receptor type and criteria for selection, is covered in guideline C. The conceptual model describes a graphical representation of a relationship between the contaminant sources, exposure pathways, and receptor, details about which are

**Table 2**
Comparisons of important elements in different ERA guidelines (the letters in this table refer to specific ERA guidelines; see Table 1).

| | Important Elements of ERA | Guideline A | Guideline C | Guideline E | Guideline U | Guideline S |
|---|---|---|---|---|---|---|
| Problem Formulation | Management goals | Considered in substantial detail | Considered in substantial detail | Not considered | Considered in limited detail | Not considered |
| | Regulatory context | Considered in limited detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |
| | Review of existing site information | Considered in limited detail | Considered in substantial detail | Considered in limited detail | Not considered | Not considered |
| | Contaminants of potential concern | Considered in limited detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |
| | Factors controlling the stressors | Considered in limited detail | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in substantial detail |
| | Receptors of concern | Considered in limited detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |
| | Assessment endpoints | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |
| | Measurement endpoints | Considered in substantial detail | Considered in substantial detail | Not considered | Not considered | Considered in limited detail |
| | Conceptual model | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in substantial detail | Considered in substantial detail |
| | Lines of evidence | Considered in limited detail | Considered in substantial detail | Not considered | Considered in limited detail | Considered in limited detail |
| | Data quality objectives | Considered in substantial detail | Considered in substantial detail | Not considered | Considered in limited detail | Considered in limited detail |
| | Uncertainties | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |
| Exposure Assessment | Stressor information, distribution, release, etc. | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail | Considered in substantial detail |
| | Exposure media information | Considered in limited detail | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in substantial detail |
| | Receptor information | Considered in limited detail | Considered in substantial detail | Not considered | Considered in limited detail | Considered in substantial detail |
| | Calculations procedure of contaminant concentration in media | Not considered | Not considered | Considered in substantial detail | Not considered | Not considered |
| Effects Assessment | Types of effects assessment measures | Considered in limited detail | Considered in substantial detail | Considered in limited detail | Not considered | Considered in limited detail |
| | Stressor - Response Analysis | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in substantial detail |
| | Linkage of measures of effect to an assessment endpoint | Considered in substantial detail | Considered in limited detail | Not considered | Not considered | Considered in limited detail |
| | Calculation procedure for no-effect concentration | Not considered | Not considered | Considered in substantial detail | Not considered | Not considered |
| Risk Characterization | Approaches for risk estimation | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |
| | Risk description | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |
| | Risk evaluation | Considered in substantial detail | Considered in substantial detail | Considered in limited detail | Considered in limited detail | Considered in limited detail |

**Legend: Level of Detail Covered**

| | |
|---|---|
| Considered in substantial detail | (dark) |
| Considered in limited detail | (medium grey) |
| Not considered | (light grey) |

explained in all guidelines. Lines of evidence consider any pairing of exposure and effect measures that provides evidence for the evaluation of a specific assessment endpoint; guideline C has explained this in detail. The three main outcomes of the problem formulation phase are as follows (US Environmental Protection Agency (US-EPA), 1998):

- Assessment endpoint reflecting management goals and regulatory considerations.
- Conceptual model explaining key relationships between stressor and assessment endpoint.
- Analysis plan to characterize exposure and effects assessment.

#### 2.3.2. *Exposure assessment*

Any substance or process that can have an adverse impact on the ecosystem is termed a 'stressor' (Government of Canada, 2012). To assess the exposure of any stressor, it is important to identify the physical (density, state, etc.), chemical (solubility, toxicity, etc.) and biological (protein structure, biodegradation, etc.) properties of the stressor, which are explained in detail by guidelines A and E. Once the properties of stressors are known, the next step is to understand the characteristics of the receiving environmental media. These characteristics include certain parameters of the receiving environmental media that may affect the fate and transport of the stressor, the details about which are covered in guidelines C, E and S. The next important element is properties of the receptor, details about which are mostly covered by guidelines C and S. To estimate the concentration of the contaminant/stressor in the receiving environmental media, guideline E proposes the necessary mathematical equations. These equations can be used to calculate the concentration of the contaminant/stressor in the environmental media, once the stream containing the contaminant is discharged into the receiving media.

#### 2.3.3. *Effects assessment*

For characterizing effects of stressors, approaches based on site-specific toxicity/biological studies and indirect toxicity/biological information are considered in substantial detail by guideline C. The next important element is to analyze the response of a receptor to a particular stressor; guidelines A, C and S explain this concept in detail. To create an accurate stressor-response profile, sound and explicit linkages between assessment endpoint and measures of effects are needed. These linkages are based on professional judgment or empirical or process models; details about these approaches are covered by guideline A.

Another important element in effects assessment is an approach for deriving the predicted no-effect concentration (PNEC) of any contaminant/stressor. The PNEC is defined as a threshold concentration, above which harmful effect to the species will most likely occur. Guideline E describes two main approaches to derive the PNEC. The first is based on using assessment factors to establish the no-effect concentration. Assessment factors are used to compensate for the uncertainty associated with extrapolating the toxicity data obtained from the laboratory studies to the field environment (European Chemical Agency (ECHA), 2008b). The PNEC is calculated by dividing the toxicity test data by an appropriate assessment factor. The value of assessment factors changes, depending on the toxicity test data available for a number of species and short−/long-term toxicity test data. The second approach uses a cut-off value of a species sensitivity distribution (SSD), based on chronic toxicity data on different species. The SSD method can be used when large data sets from long-term toxicity tests for different taxonomic groups are available. Guidelines A and C have also mentioned these approaches; however, guideline E prescribes the use of specific values of assessment factors, depending on the availability of acute/chronic toxicity data and corresponding environmental media.

#### 2.3.4. *Risk characterization*

The risk characterization process involves the use of various approaches to characterize risk. These approaches include use of hazard quotient, comparisons of stressor response to exposure curve, field observation, etc. Risk description includes a weight of evidence evaluation that considers each line of evidence for exposure and effect, to render a conclusion regarding the probability and magnitude of adverse ecological impacts. In risk evaluation, uncertainty in the risk estimation is evaluated. Risk evaluation also covers the significance of risk in terms of the acceptable level under regulations, stakeholders' interests, etc. Guidelines A and C explain these approaches in substantial detail.

## 3. A generic ERA framework for EOR solutions

The framework described here outlines the four key phases of an ERA process, as explained in the selected ERA guidelines. In each of these phases, the elements shortlisted from the comparison of ERA guidelines in the previous chapter are used to suggest the ERA framework for produced water and drilling discharges to the sea and emissions of greenhouse gases (GHG) to the air. A literature search was conducted, to identify possible stressors that may have an environmental impact, due to produced water, drilling discharges and emissions to air. These stressors are then considered in describing an ERA framework for produced water, drilling discharges and emissions to air.

All chemicals (tracers, polymers, etc.) used during the implementation of EOR solutions will be a part of produced water that is to be discharged into the marine environment. As a result, produced water discharges have the greatest potential for environmental impact from the EOR solutions. However, it is also important to consider drilling discharges in an ERA of an EOR process. During the implementation of EOR solutions, such as smart water/polymer flooding, there might be a need to drill new wells. Drilling new wells generates drilling waste that adds up to the total environmental risk of implementing EOR solutions. Furthermore, producing smart water on an oil platform, the injection of polymers and the re-injection of produced water into the reservoir increase the emissions to air. Therefore, emissions to air need to be considered in the ERA framework.

### 3.1. *ERA of produced water discharges*

To quantify the risk to the marine environment from produced water discharges, we suggest the use of the framework described in Fig. 2. The main stressor considered for produced water discharges is the toxicity of the chemical compounds used during the implementation of EOR processes. Other parameters, such as bio-degradation and the bio-accumulation potential of chemical compounds, also contribute to the risk. The chemical compounds could be tracers, polymers, surfactants etc., used as a part of the EOR process. The main compartment for exposure pathways of contaminants in the produced water discharges is the water column of the marine environment. Species present in the water column might be at risk of being affected by the toxicity of chemical compounds present in the produced water discharges.

The concentration of these chemicals, defined as predicted environmental concentration (PEC), in the marine environment can be determined using an approach explained by the ECHA, 2016. As discussed previously, the PNEC can be estimated by two methods recommended by the ECHA (European Chemical Agency (ECHA), 2008b). In a case where no toxicity data is available for certain chemical compounds, the PNEC can be estimated using a quantitative structure-activity relationship (QSAR) (European Chemical Agency (ECHA), 2008a). The ECHA, 2012 defines risk characterization by the ratio PEC/PNEC. The ratio is related to the extent of the damage specific compounds can cause to the marine environment. Environmental risk is assessed by a comparison of exposure (PEC) of contaminants in produced water discharge to the sensitivity of the marine species (PNEC) for these contaminants. The higher the ratio, the higher the chemical hazard, and a higher percentage of marine species might be at risk of being affected.

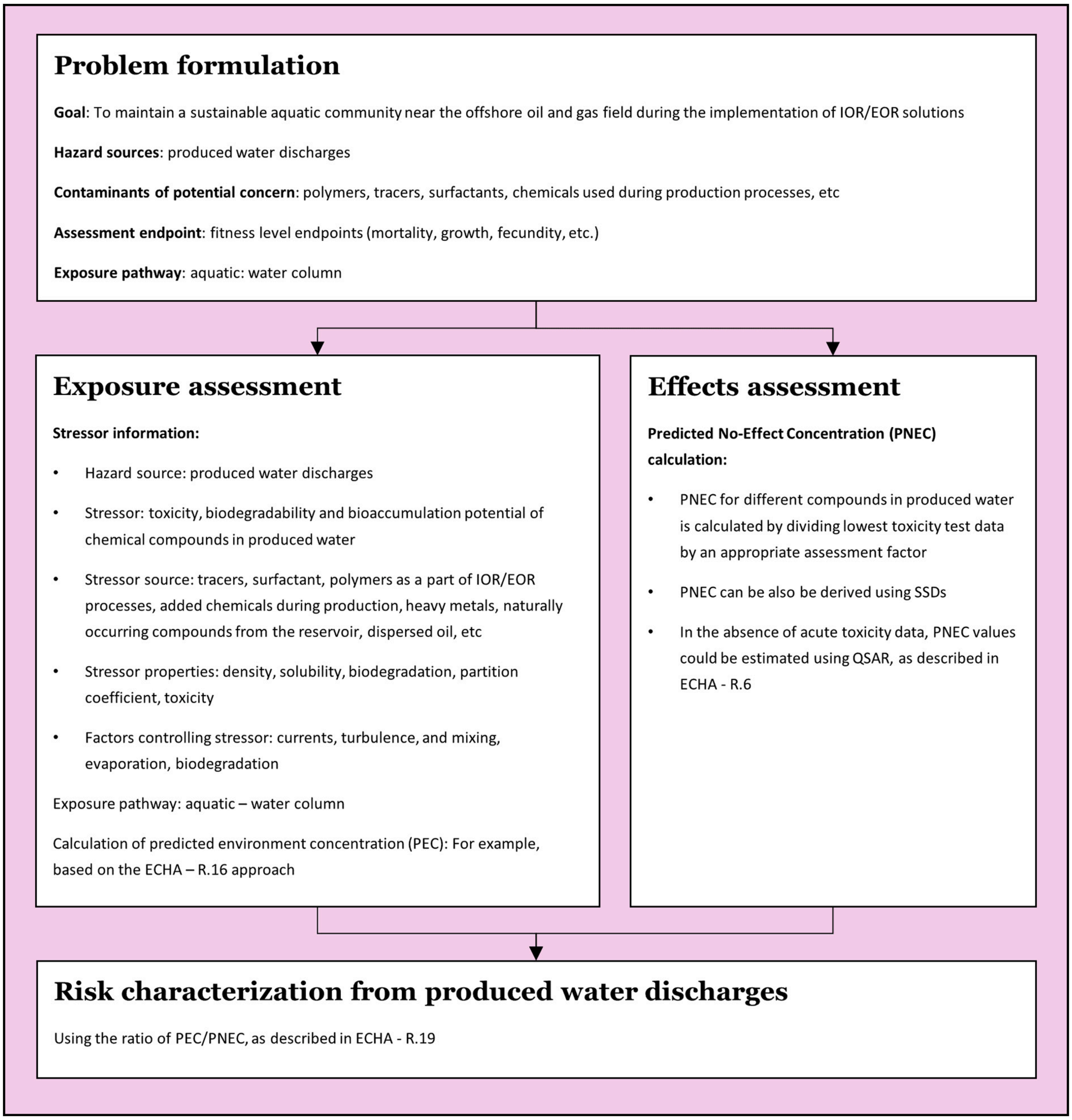


**Fig. 2.** Framework for ERA of produced water discharges from EOR solutions

### *3.2. ERA of drilling discharges*

Drilling discharges may occur as a result of drilling new injection wells, as a part of operational strategies for EOR processes. The drilling discharges can have an environmental impact, through exposure in the water column, as well as on the seafloor sediments. For assessing environmental risks associated with these impacts, we have derived the framework in Figs. 3 and 4 respectively. In the water column, the concentration of toxic components and suspended matter concentration can be considered as the stressors. The toxic components can be a result of added chemicals during the drilling process, metals and naturally occurring compounds in the reservoir (Altin et al., 2008). The source of suspended particles is mainly the cuttings and the weighting agent added during the drilling process (Smit et al., 2006b; Smit et al., 2009). In sediments, toxic component concentration, oxygen depletion, change in grain size distribution and burial of organisms could be considered as the stressors (Smit et al., 2006(a), Smit et al. (Smit et al., 2006c). The approach to characterize risk remains the same, i.e. by using the ratio of PEC and PNEC. However, for non-toxic stressors, the PEC and PNEC are redefined as predicted environmental change and predicted no-effect change, respectively (Rye et al., 2006). The PEC values for different stressors in the water column and sediments can be calculated based on the (European Chemical Agency (ECHA), 2016) (R.16) and Smith et al. (Smith et al., 2006) approach.

### *3.3. ERA for emissions to air*

The increase in emissions to air stems from an increase in energy production needed to produce smart water, injection of polymers, reinjection of produced water, etc. during the implementation of EOR processes. Increase in energy production increases emissions to air of carbon dioxide ($CO_2$), methane ($CH_4$), non-methane volatile organic carbon (nmVOC), nitrogen-oxides ($NO_x$), sulfur-oxides ($SO_x$), etc. (Norwegian Oil and Gas Association, 2019). These gaseous compounds

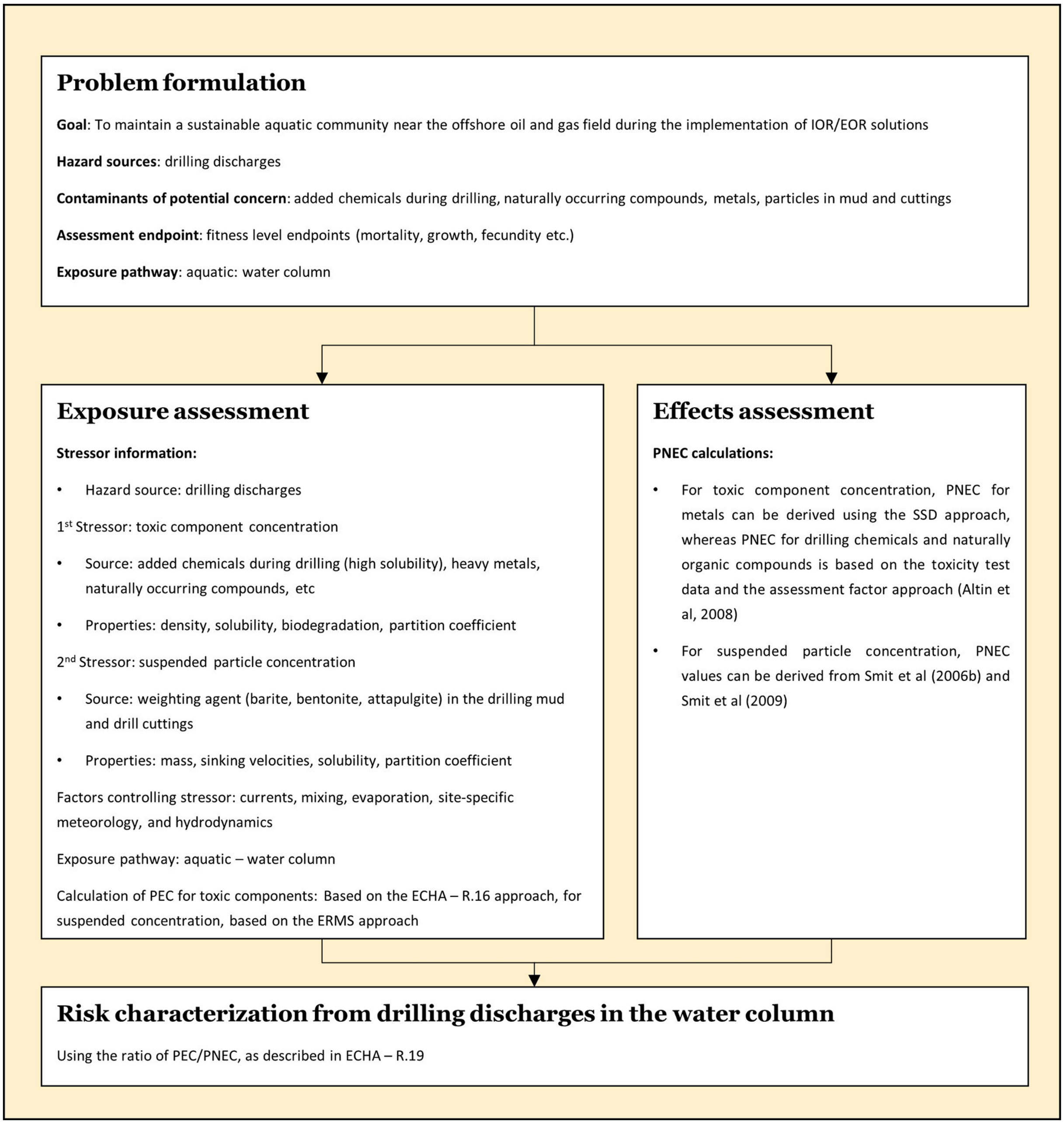


**Fig. 3.** Framework for ERA of drilling discharges in water column.

are emitted offshore and therefore they are not exposed to or pose a risk to the marine environment, wildlife or human populations directly. However, (GHG) emissions such as $CO_2$ and $CH_4$ increase global warming and cause several adverse effects, as a result of climate change (Interagency Working Grp. on Soc. Cost of Carbon, 2010). Therefore, in this study, mainly $CO_2$ and $CH_4$ emissions are considered, while assessing environmental risk from EOR solutions.

Increase in GHG emissions is known to have several adverse effects, like changes in agricultural productivity, ocean acidification, mass bleaching of corals, coastal destruction, etc., due to their global warming potential (Interagency Working Grp (Interagency Working Grp. on Soc. Cost of Carbon, 2010); Interagency Working Grp (Interagency Working Grp. on Soc. Cost of Greenhouse Gases, 2016)); (Marten & Newbold, 2012; Veron et al., 2009)). One major challenge in assessing environmental risk due to emissions to air is to derive PNEC values for GHG emissions. This is because there are several effects on the land and in the ocean from these emissions, far from the local emission locations, and it involves a highly complex carbon cycle to evaluate the contribution of a particular GHG to each of these effects. A certain threshold has been established in terms of the global concentration of $CO_2$ (450 ppm), above which coral reefs around the world will start declining (Veron et al., 2009). However, the contribution of emissions from EOR processes to this global threshold will be mostly negligible. At present, it seems that there is no direct way to assess the environmental risk of specific consequences on the land and in the ocean from GHG emissions.

There is a methodology, called the social cost of carbon (SCC), to assess some of the impacts caused by GHG emissions on land and specifically to the human population (Interagency Working Grp (Interagency Working Grp. on Soc. Cost of Carbon, 2010); Interagency Working Grp (Interagency Working Grp. on Soc. Cost of Greenhouse Gases, 2016)). SCC is an estimation of economic damage associated with an increase in carbon emissions each year (Interagency Working Grp. on Soc. Cost of Carbon, 2010). SCC is calculated by integrated assessment models, considering net changes in agricultural productivity, human

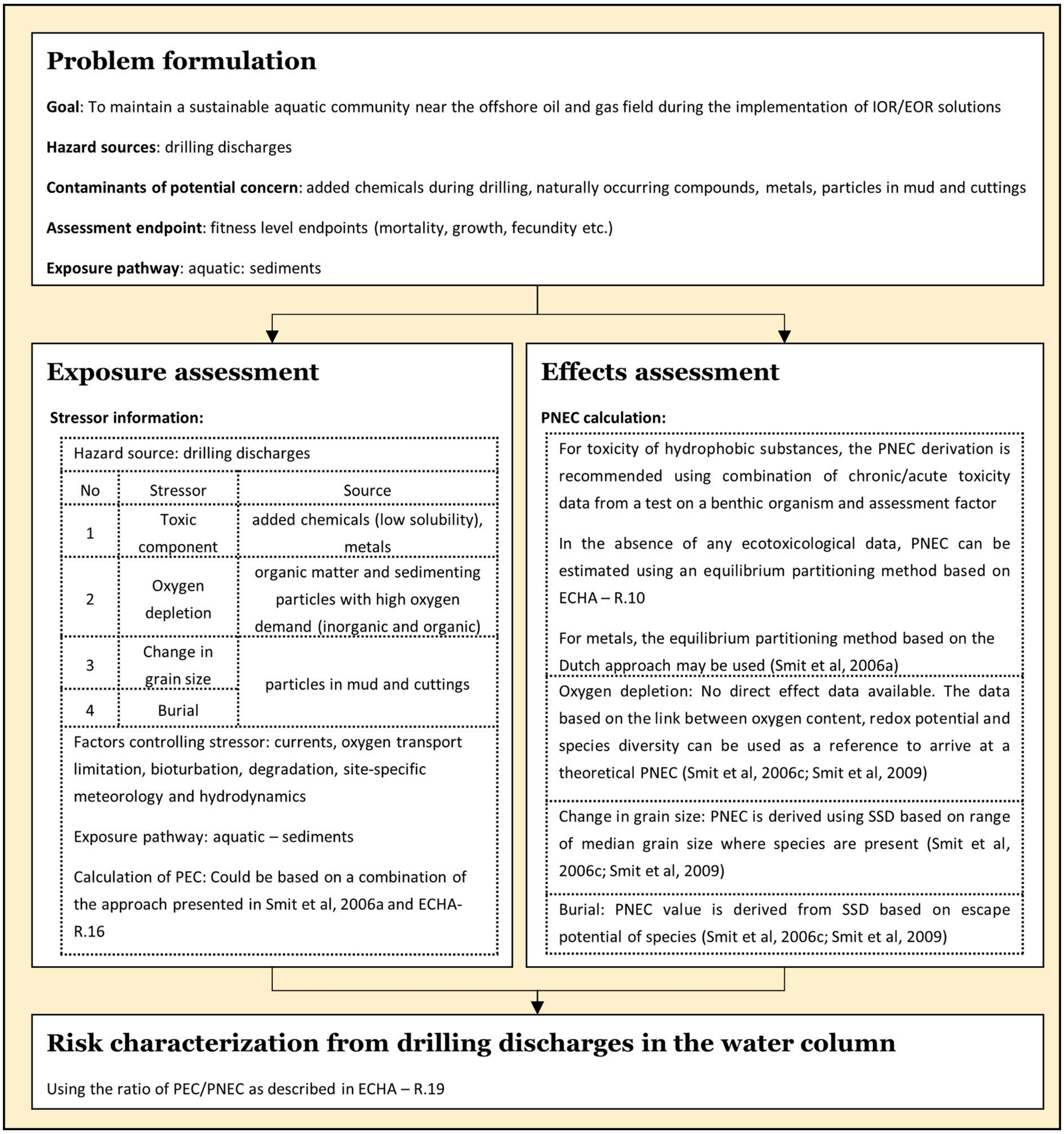


**Fig. 4.** Framework for ERA of drilling discharges in sediments

health, property damage from increased flood risk, etc. due to global warming (Interagency Working Grp. on Soc. Cost of Carbon, 2010). Therefore, we suggest an approach to quantify risk in terms of SCC, as described in Fig. 5. Emissions to air, mainly $CO_2$ and $CH_4$, can be quantified (PEC) using a method based on the use of an emission factor. The emission factor method uses a factor that can be multiplied with the volume and type of fuel combusted, to quantify different emissions. Guidelines available from the GHG protocol can be used to quantify these emissions (Gillenwater, 2005).

### *3.4. Compliance with policies for the marine environment in the European union*

Environmental policies usually provide guidelines about the best environmental practices for assessing and reducing environmental impacts from anthropogenic activities. In recent years, the EU has emerged as being in the forefront in advocating and implementing various multilateral environmental agreements (Kelemen & Knievel, 2015; Le Cacheux & Laurent, 2015). Therefore, environmental policies applicable to the marine areas of the EU have been reviewed. Table 3 provides an overview of international conventions that are currently in practice for the protection of the marine environment around Europe (Regional Sea Convention (RSC), 2019). These conventions, along with other EU regulations, such as the Common Fisheries Policy (CFP) and Water Framework Directive (WFD), protect the marine environment from specific sources of pollution (European Union (EU) Coastal and Marine Policy, 2019). For instance, CFP regulates fisheries, while WFD regulates the flow of nutrients and chemicals into the sea (Smit et al., 2007).

Of all the conventions mentioned in Table 3, OSPAR provides the most comprehensive guidelines for assessing environmental risks and reducing pollution from offshore oil and gas activities. OSPAR is a collaboration between 15 governments and the European Union (EU), to

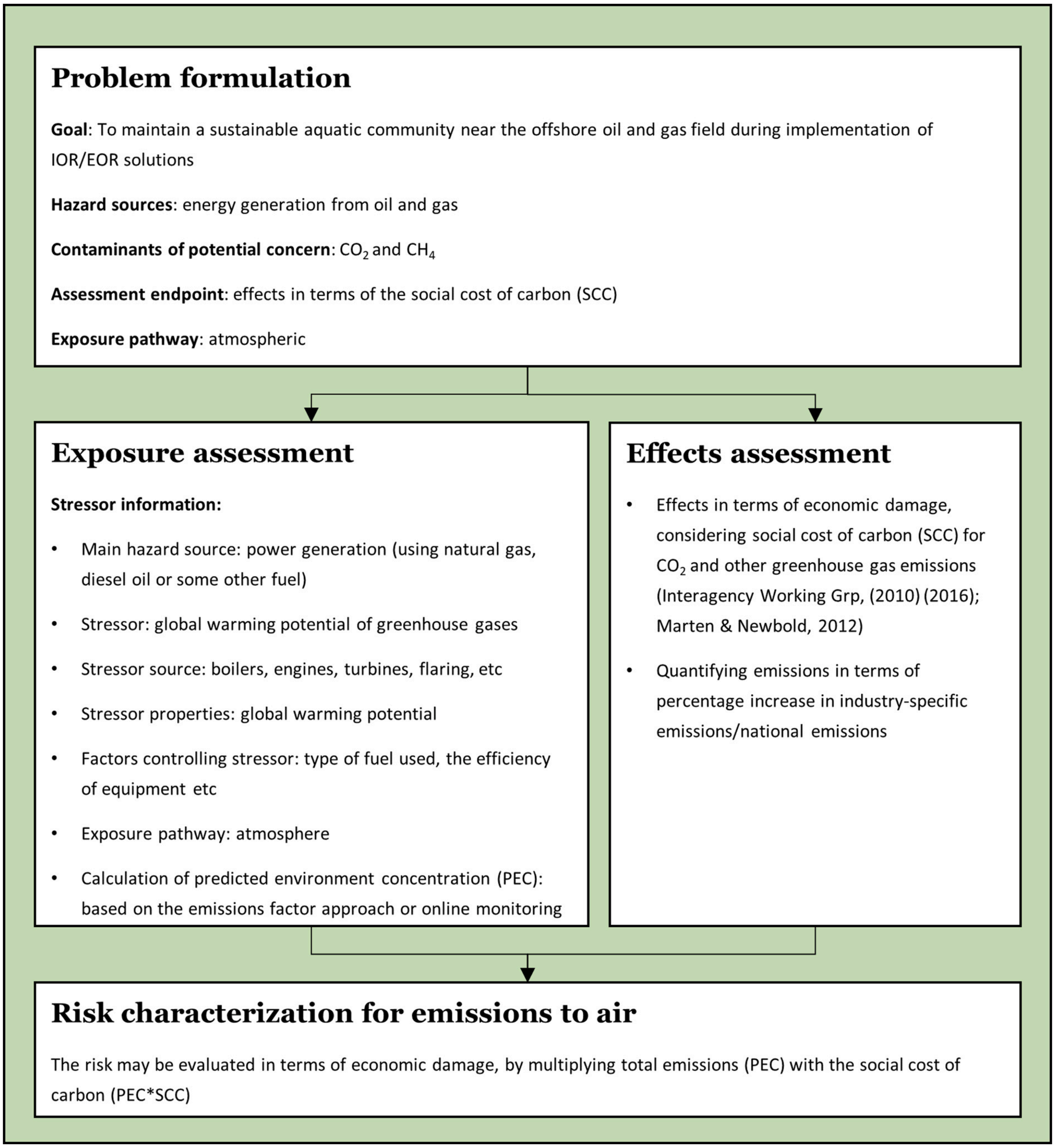


**Fig. 5.** Framework for ERA of emissions to air.

protect the marine environment of the North-East Atlantic. The OSPAR Commission provides guidelines for produced water management, drill cuttings' management, and the use of chemicals for offshore oil and gas operations (Oslo and Paris Commission (OSPAR), 2019).

- Produced water discharges: OSPAR lays down the procedure for implementing a Risk-Based Approach (RBA) to manage produced water discharges from offshore oil and gas installations.
- Drilling discharges: OSPAR has provided guidelines for the use of drilling fluids and the disposal of drill cuttings' residue, according to BEP.
- Use of chemicals: OSPAR has adopted a harmonized mandatory control system (HMCS) for using chemicals for offshore operations. The HMCS requires the data on parameters such as biodegradability, bioaccumulation and toxicity, for chemicals to be used offshore. Chemicals that are above a certain threshold of these parameters are not permitted to be used in offshore operations.

Those countries that are part of the OSPAR agreement have their own program for implementing the above-mentioned guidelines from the OSPAR Commission (Department of Energy and Climate Change, 2014; de Vries & Tamis, 2014). These implementation programs recommend the use of an internationally recognized simulation tool for the ERA of oil and gas activities. In the UK's implementation of OSPAR's RBA, simulation tools such as DREAM, PROTEUS and MIKE are mentioned for conducting ERAs (Department of Energy and Climate Change, 2014). In the Dutch implementation program, DREAM and DELF3D are mentioned for conducting ERAs (de Vries & Tamis, 2014).

A comparison study by (de Vries & Karman, 2009) of all the above-mentioned simulation tools suggests the DREAM model to be the most

**Table 3**
Main international agreements for the protection of the marine environment in and around Europe.

| Convention | Geographical area protected | Main sources of pollution addressed |
|---|---|---|
| HELCOM (Helsinki Commission) | Baltic Sea marine environment | agriculture, fisheries, industrial release, marine litter, shipping, etc. |
| OSPAR (Oslo and Paris Commission) | North-east Atlantic marine environment | hazardous substances, offshore oil and gas, offshore wind, shipping, aquaculture, radio-active substances' discharge, etc. |
| The Barcelona Convention | Mediterranean Sea marine environment | pollution from land-based sources, dumping protocol from ships and aircraft, pollution from ships, offshore exploration, etc. |
| The Bucharest Convention | Black Sea marine environment | chemical pollution from land-based sources and maritime transport, achieving sustainable management of marine living resources. |

comprehensive tool for assessing environmental risk from produced water discharges. *"The DREAM model currently provides a convenient way of determining the extent of potential effects"* ((de Vries & Karman, 2009), p. 30). The stressors described in the framework for produced water and drilling discharges in this study are defined, and their effect can be estimated, in the DREAM model. To quantify the risk associated with produced water and drilling discharges, a risk-based environmental management tool, called an environmental impact factor (EIF), is incorporated within DREAM (Johnsen et al., 2000; Reed & Hetland, 2002; Smit et al., 2007; Smit et al., 2011). A detailed description of the methodology and EIF calculations for produced water discharges is available from Johnsen et al. (Johnsen et al., 2000); for drilling discharges, it is available from Smith et al. (Smith et al., 2006).

## 4. Discussion

A comparison of ERA guidelines shows that the information about shortlisted elements in the problem formulation and risk characterization phases are largely covered by guidelines from the US and Canada. The details about calculation procedures for assessing the exposure of contaminants (PEC) and the procedure for calculating no-effect concentration (PNEC) in effects assessments is covered by the ECHA guidelines. Based on the shortlisted elements from the guidelines, the ERA framework is suggested for produced water, drilling discharges and emissions to air. The procedure described in the framework can be used for assessing risk to the environment from the implementation of EOR solutions. Moreover, according to a recent study, the highest number of contaminants discharged in the sea comes from offshore oil and gas industry, followed by shipping, mariculture, dredging and dumping activities, offshore renewable energy devices, shipwrecks and seabed mining (Tornero & Hanke, 2016). The ERA framework suggested in this study could also form a basis and can be applicable for assessing environmental risk from other anthropogenic activities mentioned above.

Most of the polymer flooding projects around the world have shown promising results in increasing the oil recovery (Standnes & Skjevrak, 2014). However, until now, the majority of these projects were implemented onshore. Therefore, limited knowledge is available regarding the amount of back produced polymer, their treatment and if discharged their behavior in the marine environment, if these polymer floods are to be implemented offshore (Standnes & Skjevrak, 2014; Thomas et al., 2012). Some of the most commonly used polymers for EOR processes are acrylamide-based polymers that are shown to have a low degradation in the environment (Guezennec et al., 2015). These polymers exhibit low toxicity at environmentally relevant concentrations in the marine environment, however, their low degradation rate could be a challenge (Farkas et al., 2020; Hansen et al., 2019). Currently available simulation tools such as DREAM focus on toxicity of chemicals for assessing environmental risk (Johnsen et al., 2000; Smit et al., 2007; Smit et al., 2011). Therefore, risk related to low degradation rates of polymers will not be captured by these tools. In this case, alternative methods to assess environmental risk from polymers needs to be adopted. These could include the use of ocean modelling tools such as Opendrift to track the trajectory of polymers in the marine environment (Dagestad et al., 2018). Along with this, improved knowledge and model expressions regarding de-polymerization and bio-degradation of polymers need to be developed for predicting the time for which polymers will stay in the marine environment before complete degradation.

It is important to emphasize that there are knowledge gaps regarding conducting a solid ERA of polymers. These knowledge gaps can provide opportunities for further research. As discussed previously, the behavior of polymers in the marine environment is a complex phenomenon that depends on biotic and abiotic factors contributing to the degradation. The degradation process involves the formation of different chemical compounds with varying toxicity before complete degradation. There is a study ongoing to bridge the knowledge gap of polymer degradation and the acute toxicity of degraded compounds in the marine environment ((Opsahl & Kommedal, 2021a) (a) (b) (c), unpublished results). Despite this study, the impacts from the accumulation of polymers in the marine environment over a long-time scale and the chronic toxicity of the degraded compound are currently unknown.

If these polymers are to be accepted for offshore use in the countries that are part of OSPAR commission, data about bio-accumulation, bio-degradation and aquatic toxicity needs to be submitted and approved by the relevant national competent authorities (Oslo and Paris Commission (OSPAR), 2019). For instance, in Norway, the regulation on offshore chemicals expands beyond the requirements of the OSPAR commission. Based on the eco-toxicological data, chemicals are categorized into black, red, yellow and green category, with black chemicals posing significant risk to the environment (Petroleum Safety Authority Norway, 2020). Although polymers used in the EOR process exhibit low toxicity, they will most likely fall into the red category due to their low degradation rate. If these polymers are to be approved for offshore use, a comprehensive risk assessment needs to be presented and approved by the relevant environmental authorities. Therefore, results from ERA done on the suggested framework in the current study coupled with the new method adoptions mentioned is of crucial importance. This is due to growing interest by stakeholders for implementing polymer flooding offshore, considering the significant economic potential in terms of oil recovery. Approved use of polymers offshore will likely have to be based on positive outcome of adequate risk assessment, and to achieve this it seems necessary beforehand that the process of polymer flooding is optimized to inject minimum amount of polymers in the reservoir, that the majority of the back-produced polymers are re-injected and only small amount are released in the marine environment.

For emissions of GHG, there is no standard methodology available to assess the environmental risk to the ecosystem. Although the global GHG concentration directly affects ocean acidification and coral reefs (Hooidonk et al., 2016; Veron et al., 2009), we have been unable to find an existing methodology for estimating the PNEC for GHG emissions. The reason could be that the global concentration of $CO_2$ is the result of a highly complex carbon cycle, and several processes within the carbon cycle need to be modeled to arrive at conclusions regarding environmental effects. In this study, an approach, based on SCC, is described that mainly considers the impacts of GHG emissions on the human population. However, further work needs to be done to assess the risk to the ecosystem from GHG emissions.

Finally, there are challenges in conducting an ERA of EOR processes while using the framework suggested in this study. These challenges are related to dealing with uncertainties in the risk assessment and aggregation of total risk. In the section below, these challenges are elaborated in further detail.

### *4.1. Uncertainties in ERA*

One major challenge that exists in an ERA of EOR processes is assessing and treating uncertainties at each stage of the process. The uncertainties exist in exposure assessment while estimating the PEC, and in effect assessment while estimating the PNEC. Uncertainties can lie in the estimation of the PEC for degradation products formed during the depolymerization of polymers in the marine environment. For estimation of the PNEC, the uncertainties can be due to varying toxic behavior of different compounds formed during the polymer degradation process. In order to have a concrete understanding and confidence in the ERA results, it is important to identify and address uncertainties scientifically. When uncertainties are assessed, efforts can be made to reduce the uncertainties through improved studies and knowledge generation. The ECHA has provided a guidance document on uncertainty analysis for chemical safety assessment (European Chemical Agency (ECHA), 2012) that is quite relevant in the context of the ERA of EOR processes. As per the ECHA's guidance document, the uncertainties can be categorized into three main types (European Chemical Agency (ECHA), 2012).

- Scenario uncertainty: Scenario uncertainty can be due to the accuracy of the described scenario. For instance, in assessing risk from produced water discharge, the assumption regarding the volume of discharge or concentration of polymers in the discharge can add to the uncertainties.
- Model uncertainty: This type of uncertainty can be due to the suitability of the model used for assessing environmental risk. For instance, the results from the DREAM model discussed in this paper are also subjected to uncertainty. This uncertainty can be a result of issues of accuracy in ocean currents data, wind data and algorithms used for the simulation of produced water or drilling discharge.
- Parameter uncertainty: Parameter uncertainty can be a result of errors in measurement, in the extrapolation of data, etc., for instance errors in the analytical methods used to estimate biodegradation, toxicity of polymers that are planned to be used as part of the EOR process.

The uncertainties discussed above can be due to lack of knowledge or inherent randomness within the system (European Chemical Agency (ECHA), 2012). For instance, as part of EOR processes, there will be new chemical compounds (polymers, tracers) that are planned for offshore use. There will be uncertainty about the behavior of new chemicals in the marine environment, as they have not been tested on a large scale in situ. Moreover, the degradation of polymers is a slow process, and the degradation products might be toxic (Al-Moqbali et al., 2018). There is limited knowledge about the toxicity of compounds that are formed at different stages during the degradation cycle of polymers. It is indeed a challenge to account for this type of uncertainty. Examples of inherent randomness include extrapolation of data from laboratory scale to field scale, variability in ocean currents, etc. The ECHA guidance document prescribes ways in which the uncertainty can be handled (European Chemical Agency (ECHA), 2012). Details about the procedure for handling uncertainties are not within the scope of this study.

### *4.2. Aggregation of risk*

Another challenge in the ERA of EOR solutions is to aggregate the total environmental risk from produced water, drilling discharges and emissions to air. The risk from emissions to air is inversely related to the risk of produced water discharges. For instance, if produced water is re-injected or treated, the emissions to air will increase, due to the increase in power requirement for running pumps and the treatment units for produced water. If not re-injected/treated and discharged to the marine environment, the risk to the marine environment will increase. It is also difficult to compare risk from produced water and from drilling discharges, as they do not have similar units of expression. The risk from drilling discharge on sediment is usually assessed based on the area impacted, while the risk from produced water discharge is assessed based on the volume of water impacted. Moreover, the risk from produced water discharge can be of a relatively short-term nature because of the biodegradation and dilution of chemicals in the water column. The risk from drilling discharges on sediments tends to be long-term, in most cases, as it might change the sediment structure and other properties for a longer period of time. Furthermore, the discharge of produced water and of drilling waste differ in time and space. One alternative for aggregating risk could be an evaluation of different impacts, assessing their severity and finding a way to combine them by expert judgements. However, the comparison and aggregation of risk from produced water discharges, drilling discharges and emissions to air is a complex issue and needs further work.

## 5. Conclusion

Currently, a comprehensive framework for the ERA of EOR solutions is lacking. In this study, the main objective is to contribute towards an initial suggestion for such a framework. The framework is suggested by describing the shortlisted elements from a comparison of a set of existing ERA guidelines. The suggested framework is set to be used for an ERA of produced water, drilling discharges and emissions to air from EOR solutions. For the ERA of emissions to air, mainly GHG, currently no standard methodology is available to determine the PNEC values for GHG emissions. We suggest a methodology, based on the social cost of carbon, that considers impacts in terms of the cost to society from emissions of GHG to the atmosphere. The risk assessment framework suggested in this study could also be considered for assessing environmental risk from other anthropogenic activities in the marine environment.

It seems like currently available simulation tools might not be able to assess environmental risk from discharge of polymers in the marine environment. In this case, new tools need to be developed to assess the environmental risk of polymers. One of the challenges in assessing the total environmental risk of EOR processes is the aggregation of environmental risk from produced water, drilling discharges and emissions to air. Another challenge is uncertainties in the assessment. To have better ERA accuracy, it is important to address and treat uncertainties. One such treatment is to reduce them through improved studies and data, which has relevance for the identification of research and development tasks to develop better EOR solutions. This is particularly relevant for our main purpose, which is to guide the research and technological development priorities for more environmentally friendly EOR processes. A second purpose following this is to support decision-making for the implementation of risk-reducing measures such as the re-injection/treatment of produced water or drilling discharges etc.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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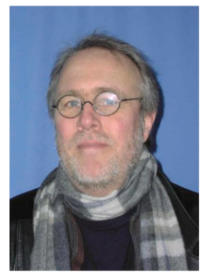

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