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The role of passive sampling in monitoring the environmental impacts of produced water discharges from the Norwegian oil and gas industry

Sarah E. Hale [a,*], Amy M.P. Oen [a], Gerard Cornelissen [a,b,c], Michiel T.O. Jonker [d], Ivar-Kristian Waarum [a], Espen Eek [a]

[a] Department of Environmental Engineering, Norwegian Geotechnical Institute (NGI), P.O. Box 3930, Ullevål Stadion, N-0806, Oslo, Norway
[b] Department of Plant and Environmental Sciences (UMB), Norwegian University of Life Sciences, 5003 Ås, Norway
[c] Department of Applied Environmental Sciences (ITM), Stockholm University, 10691, Stockholm, Sweden
[d] Institute for Risk Assessment Sciences, Utrecht University, P.O. Box 80177, 3508 TD, Utrecht, The Netherlands

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ABSTRACT

Stringent and periodic iteration of regulations related to the monitoring of chemical releases from the offshore oil and gas industry requires the use of ever changing, rapidly developing and technologically advancing techniques. Passive samplers play an important role in water column monitoring of produced water (PW) discharge to seawater under Norwegian regulation, where they are used to; i) measure aqueous concentrations of pollutants, ii) quantify the exposure of caged organisms and investigate PW dispersal, and iii) validate dispersal models. This article summarises current Norwegian water column monitoring practice and identifies research and methodological gaps for the use of passive samplers in monitoring. The main gaps are; i) the range of passive samplers used should be extended, ii) differences observed in absolute concentrations accumulated by passive samplers and organisms should be understood, and iii) the link between PW discharge concentrations and observed acute and sub-lethal ecotoxicological end points in organisms should be investigated.

1. Introduction

Current worldwide oil and gas exploration taking place offshore in sensitive coastal environments (with regards to the habitat for organisms) puts pressure on the ecosystems in these areas. Therefore operational management in the offshore oil and gas industry plays an important role in safeguarding the environment. Produced water (PW) represents the largest volume waste stream in oil and gas production operations from most offshore platforms. Around 30% of the PW discharged into the entire North Sea results from activities carried out by the Norwegian sector (Durell et al., 2006). Stringent regulations related to permissible releases from the oil and gas industry (with regards to drill cuttings, drilling fluids and produced water) exist. Owing to the large input, the North Sea is likely the most impacted and studied recipient of diffuse chemical releases from the oil and gas industry (Bakke et al., 2013). Monitoring programs have been carried out since the 1980s in order to obtain knowledge about the impact of pollutant releases, to identify problems that may arise compromising the quality of the environment, and to define measures to avoid such unintended side effects. Through monitoring programmes, the oil and gas industry obtains a wealth of descriptive data related to the environmental occurrence (distribution and fate) of pollutants as well as the ecotoxicological effects that these pollutants pose. However, the direct link between these parameters within monitoring programs is currently not comprehensively addressed and understanding of the effects that PW discharge can have on the marine ecosystem still remains challenging.

This article explores how chemical occurrence data could be better linked to ecotoxicological effects data within the current legal monitoring and reporting frameworks the Norwegian oil and gas industry must comply to. Using Norwegian legislation, water column monitoring requirements, and case studies, specific focus is given to the effects of PW discharges to seawater. Current monitoring practice, progressive monitoring methods and research needs are addressed. Norway is used as a case study and as of 2012, Norway was the world's third largest gas exporter and the tenth largest exporter of oil, producing 226 million cubic meters of oil equivalent (Sm^3) (Ministry of Petroleum and Energy and Norwegian Petroleum Directorate, 2013). Additionally, crude oil, natural gas and pipeline services represented slightly more than half of Norway's export value, with the export of petroleum products amounting to almost 100 billion USD, i.e. nearly 10 times the export value of fish (Ministry of Petroleum and Energy and Norwegian Petroleum Directorate, 2013). Monitoring practice in Norway follows a guideline document issued by the Norwegian Environment Agency

* Corresponding author.
E-mail address: sarah.hale@ngi.no (S.E. Hale).

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which was revised and updated in 2015 (Norwegian Environment Agency, 2015). A critical focus will be placed on this guideline document.

2. Composition of produced water (PW)

In 2012, around 130 million cubic meters of PW was discharged by the Norwegian offshore oil and gas industry (Norsk olje og gass, 2013), a volume which has been increasing due to aging of wells and the rising number of producing fields. PW includes both formation water (seawater or freshwater trapped with oil and gas in a geological reservoir) and injected water (seawater, freshwater and brine water, as well as added chemicals that are injected to enhance recovery of oil and gas, and to heighten operational safety) and as such contains components such as dispersed oil, aromatic hydrocarbons, alkylphenols, organic acids, heavy metals, radioactive materials and inorganic salts. The exact composition of a particular PW is closely coupled to the geological characteristics of the reservoir under exploration (Bakke et al., 2013; Utvik, 1999). The composition of different PWs have been well characterised in the literature (Utvik, 1999; Røe and Johnsen, 1996; Thomas et al., 2004). In addition to the chemicals found in PW from the formation water, several other chemicals of varying toxicity are added during operation together with the injected water (Norsk olje og gass, 2013).

The petroleum hydrocarbons (total petroleum hydrocarbons, TPH) contained within PW are the chemicals of greatest environmental concern and comprise a complex mixture of thousands of individual chemicals, including BTEX (benzene, toluene, ethylbenzene and xylenes) and PAHs (polycyclic aromatic hydrocarbons). BTEX, which represent the most abundant group of hydrocarbons, are also those that are the most volatile and owing to their rapid evaporation, their environmental effects are limited (Lee and Neff, 2011). In contract, the higher persistence and toxicity of PAHs implicates them as chemicals of environmental concern (Meador et al., 1995). The 2, 3 and 4 ring PAHs are often most environmentally abundant due to their relatively high aqueous solubility, while the higher molecular weight PAHs are generally associated with dispersed oil droplets (Faksness et al., 2004). Typically the composition of alkylphenols (APs) in PW is dominated by less alkylated C1 to C3 alkylphenols, and whilst these compounds are able to exert environmental effects, they are less toxic than the higher molecular weight and branched para alkylated compounds (Beyer et al., 2012). Naphthenic acids, when abundant in the respective crude oil are also present in the resulting PW and represent a mixture of alkyl substituted acyclic and cycloaliphatic carboxylic acids that can pose an environmental threat (Clemente and Fedorak, 2005).

3. Current environmental legislation for monitoring marine, coastal and transitional waters

The overarching legislations that are relevant to the monitoring of marine, coastal and transitional waters in the North-East Atlantic Ocean and its adjacent seas are: (1) the OSPAR Joint Assessment & Monitoring Programme (JAMP) (OSPAR Commission, 2015), (2) the EU Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC applying to coastal and marine waters) (European Parliament and Council of the European Union, 2008), and (3) the Water Framework Directive (WFD 2000/60/EC.) (European Parliament and Council of the European Union, 2000) and its daughter directive on environmental quality standards (EQS values for transitional, coastal, and territorial waters). The OSPAR Commission's strategic objective with regard to offshore oil and gas activities is to prevent and eliminate pollution caused by the offshore industry and to protect the maritime area against adverse effects, thus safeguarding human health and conserving marine ecosystems. In addition, when possible, marine areas which have already been adversely affected should be restored (OSPAR Commission, 2000). OSPAR recognises the importance of achieving synergy between the activities outlined in the JAMP and the equivalent requirements of the MSFD and WFD. Specific to the monitoring of PW, OSPAR adopted a Recommendation for a Risk-based Approach to the Management of Produced Water Discharges from Offshore Installations (RBA Recommendation) and associated Guidelines. Full implementation of these guidelines will be in 2018. The MSFD states that strategies must be developed and implemented that protect and preserve the marine environment, prevent deterioration or, where practicable, restore marine ecosystems in areas where they have been adversely affected. Strategies to prevent and reduce inputs in the marine environment, with a view to phasing out pollution must be developed. Member states are required to determine the environmental status of their water bodies, establish environmental targets and carry out monitoring programmes. The WFD applies to waters within one nautical mile from land; therefore it is less relevant in the context of PW releases.

Within these regulations, pollutant threshold concentrations that are deemed acceptable to protect marine systems (so called Environmental Assessment Criteria by OSPAR) are provided and are primarily based on aqueous toxicity data that has been recalculated to concentrations in sediments and biota by using equilibrium partitioning models (OSPAR Commission, 2004) which may lead to erroneous overestimations of risk. OSPAR does recognise the relevance of freely dissolved aqueous concentrations of nonpolar compounds for toxicity assessment based on the weight of scientific evidence showing that such concentrations represent the direct negative effect pollutants can have on organisms (Hawthorne et al., 2007; Kraaij et al., 2003). However, freely dissolved concentrations are difficult to measure, as they are often very low, because of rapid PW dilution. Therefore OSPAR requires that these pollutant concentrations be measured in biota and sediment (Commission., O., OSPAR, 2008).

4. Current environmental monitoring in the Norwegian water column

The Norwegian Environment Agency is responsible for developing guidelines for monitoring the Norwegian oil and gas industry. In 2015 they published the guideline document "Environmental monitoring of petroleum activities on the Norwegian continental shelf, M-408/2015" (Norwegian Environment Agency, 2015), replacing the guideline from 2011. Thus far, monitoring data from the implementation of this guideline is not available. Monitoring is intended to indicate whether the environmental status of the Norwegian continental shelf is stable, deteriorating or improving, due to offshore operators' activities. Monitoring of both the water column and the native benthic habitat should be carried out in accordance with this guideline. Further discussion is given here about the requirements for water column monitoring since the discharge of PW to seawater is expected to affect the water column most.

Water column monitoring should be carried out every three years and surveys should include: hydrographical measurements, chemical analyses, investigations of field transplanted organisms held in cages and investigations of wild caught organisms. Hydrographic parameters that should be measured include: conductivity, temperature, density, current direction and speed. Chemical analyses that should be carried out using passive samplers includes measuring the content of total hydrocarbons, PAHs, which includes naphthalenes, phenanthrenes and dibenzothiopenes (and these are collectively referred to as NPDs) and APs. The field transplanted organisms that should be placed in cages should be mussels, dominated by *Mytilus edulis.* Passive samplers should also be placed inside the cages in the surveyed areas and be used to quantify the exposure of the mussels. Biological parameters that should be monitored for the mussels include: size, spawning status, health, PAH and metal concentrations, chromosome damage, lysosomal membrane stability and acetylcholinesterase inhibition. Wild caught organisms should include pelagic and demersal species that live in the surveyed area and should be representative of the most important