OSPAR COMMISSION

Report on impacts of discharges of oil and chemicals in produced water on the marine environment

Offshore Oil & Gas Industry Series

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Assessment of impacts on the marine environment of discharges of oil and chemicals in produced water from the offshore oil and gas industry and draft summary of results of Seabed Monitoring Programs

OSPAR Convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the "OSPAR Convention") was opened for signature at the Ministerial Meeting of the former Oslo and Paris Commissions in Paris on 22 September 1992. The Convention entered into force on 25 March 1998. The Contracting Parties are Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Convention OSPAR

La Convention pour la protection du milieu marin de l´Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d´Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998. Les Parties contractantes sont l´Allemagne, la Belgique, le Danemark, l´Espagne, la Finlande, la France, l´Irlande, l´Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume- Uni de Grande Bretagne et d´Irlande du Nord, la Suède, la Suisse et l´Union européenne

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Executive summary

The continuous discharges of PW are an environmental concern, as they represent the largest source of crude oil contamination to sea from offshore oil and gas operations. In addition to the natural pollutants in the oil, potentially toxic hazardous production chemicals are also discharged. The impact of these discharges on the offshore ecosystem is assessed in this report (JAMP Product O-2) as one of several steps in preparation of input to the OSPAR Quality Status Report 2023 for the offshore oil & gas sector (JAMP Product O-5).

The assessment should be built on the Intermediate Assessment 2017 for the offshore oil & gas sector, on existing data and information from e.g. Water Column Monitoring (WCM) reports as well as other data made available from the Contracting Parties. In addition to this, information from peer-reviewed research articles, publicly available reports summarizing scientific research as well as reports from surveys of PW impact in the water column has been included. Finally and in addition to WCM, data from seabed monitoring programs around offshore platforms have been included, as interactions between water column and seabed cannot be dismissed. A summary of available publications from the last decade have been summarized after the main report on produced water. The draft report was commented by the Contracting parties in spring 2020 and, after a major revision, again in November 2020, which has led to further revisions in the present version of the report.

The volume of dispersed oil discharged as either produced or displacement water has decreased 19% between 2009 and 2018 and has the last three years been stable at approximately 4000 tonnes of dispersed oil. The average concentration of the dispersed oil in the discharged water has through the same period remained largely steady around 13 mg/L as compared to the performance standard in OSPAR Recommendation 2001/1 (as amended) 30 mg/L.

Naturally occurring components in produced water with a high risk characterization ratio include substances belonging to the groups of phenols, alkylphenols, and naphthenic acids. The group of alkylphenol substances include individual substances with endocrine disrupting properties in aquatic organisms. Naphthenic acids include substances that are suspected to have endocrine disrupting effects. High risk ranges are also noted for the BTEX-substances (Benzene, Toluene, Ethylbenzene, Xylenes), which however are expected to dissipate quickly from the water column due to evaporation. PAHs, including naphthalene, phenanthrene and dibenzothiophene (NPD) may have severe effects in the water column such as carcinogenicity, DNA damage, embryotoxicity, growth retardation, oxidative stress and narcotic effects. Several of the metals found in PW have a high toxicity to aquatic organisms and some have a potential for bioaccumulation. Produced water also contain chemicals added during processing or separation of produced oil and gas. A number of different offshore chemicals are applied and are in many cases the main contributors to the overall toxicity of the produced water.

Through the introduction of the Risk Based Approach (RBA) in OSPAR Recommendation 2012/5, the environmental risk of discharges of produced water are calculated for all installations discharging produced water to the OSPAR maritime area. The purpose of RBA is to assess the environmental risk posed by discharges of oil and other substances with produced water, with the aim of finding appropriate measures to reduce the risk to acceptable levels, where the calculations show it is not adequately controlled. While RBA cannot be used as basis for an assessment of the actual impact of PW in the marine environment, the results can be used as a tool to target the different investigations of such impacts in the sea around the offshore installations.

Toxicity studies have been conducted at several trophic levels of marine organisms (e.g. bacteria, algae, zooplankton, bivalves, fish), especially from Norwegian ecosystems.

Controlled laboratory studies show that PAH contaminants from oil contamination may induce cardiac defects impacting the fitness of fish fry in several critical ways including reduced swimming performance, prey capture, and prey avoidance, with repercussions for survival and possibly for population recruitment. Haddock is believed to be particularly vulnerable to oil during early life stages because embryo surface (chorion of the egg) is very sticky and haddock eggs were found to adsorb dispersed oil droplets to a much higher degree than eggs from the Atlantic cod. It remains to be seen whether cardiac toxicity can be induced in fish, eggs or larvae drifting through an offshore plume of

PW. Cod eggs, larvae and fry effectively absorb alkylphenols from produced water, and the earliest life stages (eggs and larvae) may be more exposed to toxic effects of the compounds as they have less capacity to metabolise and excrete the short chain alkylphenols compared to juvenile and adult fish, which excrete via bile over a period of hours or a few days.

More field-realistic studies used fish caged in the main pollution plume, which were investigated for chemical content incl. PAHs and alkyl phenols as well as biomarkers such as DNA adducts and histological effects. It was concluded from these findings that the fish had been exposed to produced water. However, elevated levels of PAH and biomarkers of exposure have not been identified consistently in wild fish, whether caught outside, or in, production field areas in the North Sea. An explanation for this could be that some fish species are actively avoid plumes containing elevated levels of PAHs, which makes it difficult to assess the impact on wild fish population from observations made on caged fish. The typical modest responses on the possible PW exposure found in wild fish in combination with the environmental risk assessments of PW discharges offshore, points at a low-risk situation for PW discharges in the OSPAR area.

Similar to fish, mussels kept in cages in a PW plume relatively close (some hundred meters to a few kilometres) to the PW discharge point can be confirmed exposed to PW by findings of accumulated PAHs and modest responses such as stress indicated by histopathological analyses of mussels' digestive gland. The observed levels and responses decreased with the distance from the platform. Caged blue mussels (*Mytilus edulis*) were found to be compensating for the stress, maintaining reproductive development such as spawning status. The mechanism for compensation is unclear, but could be due to an increase in phytoplankton growth caused by fertilization (with e.g. ammonia in PW) or a toxicity-related reduction in planktonic grazing pressure, both leading to increased food availability to mussels.

There is no consensus on which biomarkers to use for zooplankton, brine shrimp (*Artemia salina*) being a standard test organism. Neither zooplankton nor phytoplankton (algae) have yet been proven to be particularly sensitive.

It is generally accepted that organism effects are observed at PW concentrations corresponding to a dilution of less than 1000 times. This corresponds roughly to a distance of less than 1000 m from the discharge point depending on the discharge rate, water depth, local currents and other environmental factors. Based on laboratory results where the test organisms are exposed to constant concentrations over several days as well as studies with caged animals placed in the PW plume, acute effects can be expected at such concentrations. Effects at lower concentrations are observed, however, after weeks of exposure. Such long exposure times are, however, not relevant under environmental conditions where organisms in the water column move actively, and the direction of the plume may be change over time due to tide, currents, and wind. Sessile organisms are also expected to rarely experience constantly high exposure levels.

Despite the large volumes of PW released, the impact of the constituents appears to be low and mainly seen at biomarker level, which makes it important to be able to translate the biomarker-indicated exposure of individuals into an effect to the organism and ultimately an impact on the population. The causality between the biomarkers and toxic effects at organism and population levels remains to be proven. Furthermore, other anthropogenic factors are difficult to exclude when assessing the impact of PW in marine ecosystems. Whilst, the conclusions from OSPAR Quality Status Report 2010 are still valid: "*While some biomarker responses to contaminants in produced water can be observed, indicating exposure to produced water, no causal relationship has been identified that can link these observations to impacts to the organism, populations or the ecosystems as such.*", further investigations are needed to establish, whether such relationships exist.

It could be considered to include additional species from the water column in further studies on the impact of PW on aquatic ecosystems. A better knowledge on the impact at community level could be obtained by use of a mesocosm set-up with natural water column species. Such data could be used to quantify the impact by modelling of the mortality among different plankton species present in the water column passing a platform area.

After discharge PW is generally effectively diluted in the water phase. However, hydrophobic chemicals may adsorb to sediment, especially in shallow water or by a downward trajectory of the PW plume. The sediments of the seabed may also be exposed indirectly via sedimentation of adsorbed fractions. Sediments near offshore oil and gas platforms contain the hydrophobic components present in PW, although the source can also be drilling mud or drill cuttings. Both Danish and Norwegian studies observe that the sediment concentration of petrogenic PAHs increases in areas close to the studied platforms. However, at 70% of the stations, the dominant form of PAH in the sediment surface was pyrogenic, indicating that the main sources are the intensive maritime traffic, industrial activity and coastal cities in the region. The sediment samples around the Danish platforms were scored with biological diversity and evenness descriptors. Although low scores were observed at one platform at a distance up to 1500m 5 years after drilling operations, the general conclusion was that the environmental status near the Danish platforms is good. A similar conclusion was reached after the latest investigations in 2018. As such, changes to the seabed fauna and quality are local and short-term and the seabed is resilient to disturbances associated with oil and gas operational discharges.

Récapitulatif

Les rejets continus d'eau de production sont préoccupants sur le plan de l'environnement, car ils représentent la plus vaste source de contamination du milieu marin par le pétrole brut provenant des opérations pétrolières et gazières offshore. En plus des polluants naturels présents dans les hydrocarbures, des produits chimiques de production potentiellement toxiques et dangereux sont également rejetés. L’impact de ces rejets sur l’écosystème au large est évalué dans ce rapport (Produit JAMP O-2) ; il s'agit d'une des étapes de préparation des contributions au Bilan de santé (QSR) 2023 d'OSPAR pour le secteur pétrolier et gazier offshore (Produit JAMP O-5).

L’évaluation devrait s’appuyer sur l’Évaluation intermédiaire de 2017 pour le secteur pétrolier et gazier offshore, sur des données et informations existantes provenant, par exemple, de rapports de surveillance de la colonne d’eau, ainsi que sur d’autres données mises à disposition par les Parties contractantes. Des informations provenant d’articles de recherche évalués par des pairs, de rapports accessibles au public récapitulant la recherche scientifique, ainsi que de rapports d’études sur l’impact de l'eau de production dans la colonne d’eau, ont également été incluses. Enfin, en plus de la surveillance de la colonne d’eau, des données issues de programmes de surveillance du fond marin autour des plates-formes offshore ont été incluses, car les interactions entre la colonne d’eau et le fond marin ne peuvent être ignorées. Les publications disponibles couvrant la dernière décennie sont récapitulées après le rapport principal sur l’eau de production. Les Parties contractantes ont fait part de leurs observations concernant le projet de rapport au printemps 2020, puis de nouveau en novembre 2020 après une révision majeure, et suite à cela, de nouvelles révisions ont été incluses dans la version actuelle du rapport.

Le volume d'hydrocarbures dispersés rejetés sous forme d’eau de production ou d’eau de ballast a diminué de 19 % entre 2009 et 2018 et il est resté stable au cours des trois dernières années, soit environ 4 000 tonnes d'hydrocarbures dispersés. Au cours de la même période, la concentration moyenne des hydrocarbures dispersés dans l’eau rejetée est restée essentiellement stable, soit environ 13 mg/l, comparativement à la norme de performance énoncée dans la Recommandation OSPAR 2001/1 (telle que modifiée), qui est de 30 mg/l.

Les composants naturels de l’eau de production dont le rapport de caractérisation correspond à un risque élevé comprennent des substances appartenant aux groupes des phénols, des alkylphénols et des acides naphténiques. Le groupe des alkylphénols comprend des substances individuelles ayant des propriétés de perturbation endocrinienne dans les organismes aquatiques. Les acides naphténiques comprennent des substances suspectées d’avoir des effets perturbateurs endocriniens. On note aussi des plages correspondant à un risque élevé pour les substances BTEX (benzène, toluène, éthylbenzène, xylènes) ; celles-ci devraient toutefois se dissiper rapidement à partir de la colonne d’eau en raison de l’évaporation. Les hydrocarbures aromatiques polycycliques (HAP), comprenant le naphtalène, le phénanthrène et le dibenzothiophène (NPD), peuvent avoir des effets sévères dans la colonne d’eau, tels qu'une cancérogénicité, une altération de l’ADN, une embryotoxicité, un retard de croissance, un stress oxydatif et des effets narcotiques. Plusieurs des métaux présents dans l'eau de production ont une toxicité élevée pour les organismes aquatiques et certains ont un potentiel de bioaccumulation. L’eau de production contient également des produits chimiques ajoutés durant le traitement ou la séparation du pétrole et du gaz extraits. Un certain nombre de différents produits chimiques d'offshore sont utilisés et dans de nombreux cas, ce sont les principaux contributeurs à la toxicité globale de l’eau de production.

Grâce à l’introduction de l’Approche basée sur le risque (RBA) dans la Recommandation OSPAR 2012/5, le risque environnemental des rejets d’eau de production est calculé pour toutes les installations rejetant de l’eau de production dans la zone maritime d'OSPAR. La RBA a pour objectif d’évaluer le risque environnemental posé par les rejets

d’hydrocarbures et d’autres substances avec l’eau de production, dans le but de trouver des mesures judicieuses pour ramener le risque à des niveaux acceptables, lorsque les calculs montrent que ce risque n’est pas adéquatement maîtrisé. Bien que l'on ne puisse pas se fonder sur la RBA pour évaluer l’impact réel de l'eau de production dans le milieu marin, on peut se servir des résultats pour cibler les différentes études de ces impacts dans le milieu marin autour des installations offshore.

Des études de toxicité ont été menées sur des organismes marins à plusieurs niveaux trophiques (par exemple les bactéries, les algues, le zooplancton, les bivalves, les poissons), en particulier à partir d'écosystèmes norvégiens.

Des études contrôlées en laboratoire montrent que les contaminants HAP provenant d'une contamination par des hydrocarbures peuvent induire des malformations cardiaques ayant une incidence sur la condition physique des alevins, de plusieurs façons critiques, entre autres une diminution des performances de nage, de la capture des proies et de l’évitement des prédateurs, avec des répercussions sur la survie et peut-être sur le recrutement des populations. On pense que l’aiglefin est particulièrement vulnérable aux hydrocarbures aux premiers stades de sa vie, car la surface de l’embryon (chorion de l’œuf) est très collante, et on a constaté que les œufs d’aiglefin adsorbaient beaucoup plus les gouttelettes d'hydrocarbures dispersés que les œufs de morue de l’Atlantique. Il reste à voir si une toxicité cardiaque peut être induite chez des poissons, des œufs ou des larves dérivant en mer à travers un panache d'eau de production. Les œufs, les larves et les alevins de morue absorbent efficacement les alkylphénols à partir de l’eau de production, et les poissons aux premiers stades de leur vie (œufs et larves) pourraient être plus exposés aux effets toxiques des composés, en raison de leur moindre capacité à métaboliser et à excréter les alkylphénols à chaîne courte que les poissons juvéniles et adultes, qui les excrètent par la bile en quelques heures ou en quelques jours.

Des études reflétant mieux la situation réelle ont été menées en plaçant des poissons en cage dans le panache de pollution principal, et en examinant les substances chimiques présentes dans ces poissons, y compris les HAP et les alkylphénols, ainsi que des biomarqueurs tels que les produits d'addition à l'ADN et les effets histologiques. Ces résultats ont permis de conclure que les poissons avaient été exposés à de l’eau de production. Cependant, on n'a pas rencontré constamment des niveaux élevés de HAP et de biomarqueurs d’exposition chez les poissons sauvages, qu’ils aient été capturés à l’extérieur, ou à l'intérieur, des champs de production en mer du Nord. Cela pourrait s’expliquer par le fait que certaines espèces de poissons évitent activement les panaches contenant des niveaux élevés de HAP, ce qui rend difficile l’évaluation de l’impact sur la population de poissons sauvages à partir d’observations effectuées sur des poissons en cage. Les réponses généralement modestes à une exposition possible à l'eau de production que l'on a rencontrées chez les poissons sauvages, conjointement avec les évaluations des risques environnementaux que présentent les rejets d'eau de production en mer, semblent indiquer une situation à faible risque en ce qui concerne les rejets d'eau de production dans la zone d'OSPAR.

Comme pour les poissons, on peut confirmer l'exposition à de l'eau de production de moules placées dans des cages maintenues dans un panache d'eau de production relativement proche (de quelques centaines de mètres à quelques kilomètres) du point de rejet d'eau de production, quand on trouve des HAP accumulés et en présence de réponses modestes, telles qu'un stress indiqué par des analyses histopathologiques de la glande digestive des moules. Les niveaux et les réponses observés ont diminué au fur et à mesure qu'on s'éloignait de la plate-forme. On a constaté que les moules communes (Mytilus edulis) placées dans des cages compensaient le stress, en maintenant leur développement reproductif, par exemple pour la ponte. On ne sait pas très bien quel est le mécanisme de cette compensation, mais elle pourrait résulter d'une augmentation de la croissance du phytoplancton sous l'effet d'une fertilisation (par exemple par de l’ammoniac présent dans l'eau de production), ou d'une réduction de la pression de pâturage sur le plancton liée à la toxicité, tous deux entraînant une augmentation de la disponibilité alimentaire pour les moules.

Il n’y a pas de consensus sur les biomarqueurs à utiliser pour le zooplancton, l'artémie (Artemia salina) étant systématiquement utilisée pour les tests sur les organismes. Ni le zooplancton ni le phytoplancton (algues) ne se sont encore révélés particulièrement sensibles.

Il est généralement admis que des effets sur les organismes sont observés à des concentrations d'eau de production correspondant à une dilution inférieure à 1 000 fois. Cela correspond approximativement à une distance inférieure à 1 000 m du point de rejet en fonction du débit de rejet, de la profondeur de l’eau, des courants locaux et d’autres facteurs environnementaux. D’après les résultats des tests en laboratoire, pour lesquels les organismes sont exposés à des concentrations constantes pendant plusieurs jours, ainsi que des études pour lesquelles des animaux en cage sont placés dans le panache d'eau de production, on peut s'attendre à des effets aigus à de telles concentrations. On observe cependant des effets à des concentrations plus faibles, après plusieurs semaines d'exposition. Toutefois, ces longues durées d'exposition ne correspondent pas à des conditions environnementales où les organismes rencontrés dans la colonne d'eau se déplacent activement, et où la direction du panache peut changer dans le temps sous l'effet de la marée, des courants et du vent. En outre, les organismes sessiles devraient rarement rencontrer des niveaux d'exposition constamment élevés.

Malgré les volumes importants d'eau de production qui sont rejetés, l'impact des constituants semble faible et on l'observe principalement au niveau des biomarqueurs ; il est donc important de pouvoir traduire l'exposition indiquée par les biomarqueurs des individus en un effet sur l'organisme et, en fin de compte, un impact sur la population. La causalité entre les biomarqueurs et les effets toxiques au niveau des organismes et des populations reste à prouver. En outre, il est difficile d'exclure d'autres facteurs anthropiques lorsqu'on évalue l'impact de l'eau de production dans les écosystèmes marins. Les conclusions du Bilan de santé 2010 d'OSPAR : « Bien que l'on puisse observer certaines réponses des biomarqueurs aux contaminants présents dans l'eau de production, indiquant une exposition à l'eau de production, on n'a identifié aucun lien de cause à effet qui pourrait faire correspondre ces observations à des impacts sur les organismes, les populations ou les écosystèmes en tant que tels » restent valables, cependant des études supplémentaires sont nécessaires pour établir si ces liens existent.

On pourrait envisager d'inclure d'autres espèces présentes dans la colonne d'eau dans des études supplémentaires concernant l'impact de l'eau de production sur les écosystèmes aquatiques. On pourrait améliorer les connaissances sur l'impact au niveau communautaire en utilisant un mésocosme avec des espèces naturellement présentes dans la colonne d'eau. Ces données pourraient servir à quantifier l'impact, en modélisant la mortalité parmi les différentes espèces de plancton présentes dans la colonne d'eau passant à proximité d'une plate-forme.

Après avoir été rejetée, l'eau de production est en général diluée efficacement dans la phase aqueuse. Cependant, des substances chimiques hydrophobes peuvent être adsorbées dans les sédiments, en particulier dans les eaux peu profondes ou quand le panache d'eau de production est orienté vers le bas. Les sédiments du fond marin peuvent aussi être exposés indirectement par sédimentation de fractions adsorbées. Les sédiments à proximité des plates-formes pétrolières et gazières offshore contiennent les composants hydrophobes présents dans l'eau de production, bien que la source puisse également être des boues de forage ou des déblais de forage. Dans des études danoises et norvégiennes, on a constaté que la concentration sédimentaire de HAP pétrogénétiques augmentait dans les zones proches des plates-formes étudiées. Cependant, dans 70 % des stations, la forme dominante de HAP à la surface des sédiments était pyrogénétique, ce qui indique que les principales sources sont le trafic maritime intense, les activités industrielles et les villes côtières de la région. Les échantillons de sédiments autour des plates-formes danoises ont reçu des scores basés sur des descripteurs de diversité et d'uniformité biologiques. Bien qu'on ait obtenu des scores bas pour une plate-forme à une distance atteignant 1 500 m, 5 ans après les opérations de forage, on a généralement conclu que l'état écologique près des plates-formes danoises était bon. Une conclusion similaire a été tirée après les dernières études en 2018. Ainsi, les changements dans la faune et la qualité du fond marin sont localisés et à court terme, et le fond marin est résilient aux perturbations associées aux rejets opérationnels des installations pétrolières et gazières.

Introduction

In order to assess progress against the objectives of the Offshore Industry Strategy, the OSPAR Joint Assessment and Monitoring Programme 2014-2021, Theme O, comprises Product 02 "Assessment of impacts of discharges of oil and chemicals in produced water on the marine environment (MSFD= "pollution effects")". The assessment should build on:

- The Intermediate Assessment 2017 (IA2017) for the offshore oil & gas sector based on the Stocktaking Report from 2016.
- Existing data and information from among others Water Column Monitoring (WCM)
- Additional data if such was made available from the Contracting Parties before May 30 2019

The draft assessment report presents a summary from reports on WCM conducted by Norway and a Norwegian summary from a report on environmental effects of offshore produced water discharges evaluated for the Barents Sea as well as a Norwegian report on the results of ten years studies of long-term effects of discharges to sea from petroleum-related activities. Other relevant knowledge such as scientific reports from the previous 10 years have also been included.

The report identifies possible gaps in the present knowledge on impacts of produced water on the marine environment and recommendations on possible ways to close the gaps. Naturally Occurring Radioactive Material (NORM) is not included in the scope of the report, and reference is made to the OSPAR group on radioactivity.

The report is one of several steps in preparation for the Overall Assessment Report to be prepared for OIC 2021 as input to the OSPAR Quality Status Report 2023 (JAMP Product 0-5).

The report include quotes from relevant studies and these direct quotes are marked by italics. References in italic text are to the reference list of the quoted publication, i.e. not found in the reference section of the current document. In general, PW is used as abbreviation of Produced Water and WCM is an abbreviation for Water Column Monitoring.

To present a more complete picture of the impacts on the marine environment from oil and gas industry activities and discharges, results of Seabed Monitoring Programs (SMP) conducted by the oil & gas operators on request from the national offshore authorities are also included in the draft assessment report. It should not be seen as an indication that discharges of produced water in general have an impact on the seabed, as the probability for such impact by nature will be less likely with increasing distance and depth from where the discharges take place. It is emphasized that the report presents separate conclusions for the studies on produced water and for the complementary results of sediment monitoring.

Background information

1.1 OSPAR Quality Status Report 2010

In the 2009 OSPAR report "Assessment of impacts of offshore oil and gas activities in the North-East Atlantic" that provided input to the 2010 QRS report, the following statements were made in regard to effects and impacts in the water column (for references in the text, reference is made to the reference list in the original report):

The main impacts affecting the water column arise from the discharges of produced water and accidental spills of oil and chemicals. Assessing the impacts of these discharges on the water column is challenging, but recent research has provided evidence indicating what the impacts may be.

Water column monitoring (WCM) has been carried out to a limited extent in the OSPAR area to determine the possible effects of discharges of produced water. Water column monitoring in the Netherlands' sector in 1997 has shown an accumulation of the PAH naphthalene in blue mussels up to 1000 m from a platform (Foekema et al., 1998).

Water column monitoring started in Norway in 1999. The water column monitoring programme has two parts, both of which make use of biomarkers. Part one includes measurements of selected hydrocarbons in commercially important fish species (wild fish) every third year. Sampling is performed in a contaminated and non-contaminated area. The other part studies the fate and effect of produced water discharges and makes use of large cages with blue mussel and cod as test organisms. The cages are deployed in the vicinity of a field.

This part is carried out every third year in one region based on specific needs and focus.

Concerning the results of the mentioned WCM the following is indicated:

*Results show that caged blue mussels (*Mytilus edulis*) accumulate PAH, but that the levels decrease with increasing distance from the discharge point. Other indicators of exposure also show a gradient with stronger responses in the cages closest to the produced water discharge (Sundt et al., 2008).*

*During the monitoring in Norwegian waters in 2002 and 2005 wild cod (*Gadus morhua*), saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*) were caught and analysed. Di- and poly-aromatic hydrocarbons (NPD/PAH) have been analysed for in muscle of cod and haddock caught in the North Sea at zLing Bank/Egersund bank (reference area), Tampen, Halten Bank and in the Barents Sea (reference area) in the autumn of 2005 and concentrations were found to be below levels of quantification for fish sampled in all regions (Grøsvik et al., 2007; Klungsøyr et al., 2003).*

*Analyses of alkyl phenols in the livers of cod and haddock and the muscle of herring (*Clupea harengus*) from the Ling Bank/Egersund Bank indicated levels below limits of detection for all stations. The same results were found in earlier investigations (Klungsøyr et al., 2003) and support the findings of an assessment that concluded that the risk for estrogenic and reproductive effects in fish after alkyl phenol exposure from produced water discharges was very low (Myhre et al., 2004).*

Analyses of haddock from the Norwegian Tampen area have shown increased levels of DNA-adducts and differences in cell membrane lipid composition compared to fish from other areas. However, it is not possible to link this with the direct effects of produced water, as haddock is a bottom living species which may feed on contaminated sediments (Grøsvik et al., 2007).

Based on the results of the WCM the report concludes:

The conclusion of water column monitoring to date is that while some biomarker responses to contaminants in produced water can be observed, it is not clear what these findings mean for the individual fish, the populations or the ecosystems as such. Monitoring indicates no effect or accumulation of substances from produced water in wild fish.

and:

The conclusion so far from water column monitoring is that there can be biomarker responses, indicating exposure to produced water, but whether this exposure causes any ecological effects is yet to be determined. There are no results from monitoring so far that indicate any effects from contamination from produced water in wild fish.

In the 2010 QSR report, section 7 on Offshore Oil and Gas Industry, the following statements are made under the heading "Water column monitoring shows mostly low biological response":

Water column monitoring to determine possible effects from polycyclic aromatic hydrocarbons (PAHs) and other chemicals such as alkyl phenols discharged with produced water has been carried out to a limited extent in the OSPAR area.

Monitoring in the Netherlands' sector has shown that caged blue mussels accumulate the PAH naphthalene up to 1000 m from a platform. Water column monitoring in the Norwegian sector began in 1999 and has shown that caged blue mussels exposed to produced water discharges accumulate PAHs from the surrounding seawater. These concentrations decreased with increasing distance from the point of discharge. Levels of biological responses in caged mussels showed similar gradients to those for contaminant concentrations.

Concentrations of PAHs and alkyl phenols and measured biological responses in wild fish such as cod and haddock caught in the vicinity of offshore installations from Norwegian waters in 2002 and 2005 showed a mixed pattern mostly with no increased concentrations, but some elevated biological responses suggesting past exposure.

The results from water column monitoring are complex to interpret, particularly for wild fish for which it is not possible to link observed biological responses to a specific exposure source. Monitoring data are limited and do not yet allow conclusions to be drawn on the significance of the observed biological responses for marine life and ecosystems.

In addition to studies on the water column, the 2009 OSPAR report also addressed impacts and effects on the seabed:

As a result of contamination by OPFs and the settlement of suspended fine cuttings, benthic fauna become stressed. This results in lower diversity and the dominance of tolerant opportunistic species in several square kilometres around the well location. Areas of impact have been detected up to three kilometres away and in rare cases up to six kilometres, from the drilling locations (Olsgard and Gray, 1995). Since the ban on discharges of diesel oil-based drilling fluids and the restriction in discharge of other oil-based drilling fluids, and after the substitution of the most hazardous chemicals with less hazardous substances, the impact has significantly reduced.

It is more than 15 years since the discharge of oil contaminated drill cuttings was prohibited, but cutting piles are still present under some platforms. Studies have shown that the leakage of oil from these cuttings piles is low and their individual footprints are contracting due to natural degradation (see section 4.3 and 4.4).

The discharge of drill cuttings and water-based fluids may cause some smothering in the near vicinity of the well location. The impacts from such discharges are localized and transient but may be of concern in areas with sensitive benthic fauna, for example corals and sponges.

1.2 Impacts of certain pressures of the offshore oil and gas industry on the marine environment – stocktaking report (Offshore Industry Series report no. 684, 2016)

In order to assess progress against the objectives of the Offshore Industry Strategy, the OSPAR joint Assessment and Monitoring Programme 2014-2021 required the preparation of a stocktaking report on impacts of certain pressures of the offshore oil and gas industry on the marine environment (JAMP product O-1). The report is based on draft assessments prepared for the Offshore Industry Committee (OIC) in 2014, 2015 and 2016 on the impacts of - among others - oil and chemicals from the offshore industry on the marine environment.

The following text is an extract from the Stocktaking Report published on OSPAR's website:

Data from Norwegian water column monitoring in 2012 and 2013 shows similar findings to those presented in the QSR 2010. Significantly higher concentrations of PAH and NPD (naphthalene, phenanthrene and dibenzothiophene) were found in caged mussels located 500 m from an offshore installation in the 2012 survey. Histopathological analyses of mussels' digestive gland also indicated a minor stress condition in caged mussels located 500 m and 1000 m from the platform.

In 2013, the monitoring investigated the potential biological effects on local fish species by targeting demersal fish the impact of produced water was expected to be less marked, whilst impacts from drill cuttings and other sediment sources *on the benthos and sedentary species were likely to be greater. However, significant increases in DNA adducts, COMET tails and histological effects, and a decrease in acetylcholine esterase inhibition were observed in fish collected from around the platforms when compared to the reference location.*

In general, results from monitoring of the water column have shown some effects, such as higher concentration of PAH and NPD and some biological responses in caged organisms near the platforms. Increased levels of PAHs, alkyl phenols and measured biological responses also suggest effects in wild fish caught elsewhere in the North Sea.

In 2012, the Norwegian Research Council published the report "Long term effects of discharges to the sea from petroleum related activities - Results of ten years of research"[4]. The report stated that although production chemicals may contribute significantly to the theoretical impact when modelling the environmental risk of operational discharges, the compounds have not received particular focus in the Norwegian monitoring programmes. This emphasizes that there should be an increased focus on parameters that could detect such impacts for future water column monitoring.

Monitoring data are limited and do not allow conclusions to be drawn on the significance of the observed biological responses for marine life and ecosystems. Through the introduction of the Risk Based Approach (RBA) (OSPAR Recommendation 2012/5) the environmental risk of discharges of produced water will be calculated for all relevant installations in the OSPAR area by 2018 at the latest. The purpose of the RBA recommendation is to assess the environmental risk (e.g. expressed as PEC/PNEC) posed by discharges of oil and other substances discharged with the produced water, with the aim of finding appropriate measures to reduce the risk to acceptable levels. Risk assessment at a substance level may also help identify substances for further investigations of possible biological impacts on marine biota. The risk assessment step will not provide information on the actual impacts on marine biota, but the recommendation includes the potential for environmental monitoring in order to detect changes in the receiving environment and to verify the impact hypothesis. More data relevant to describe possible impacts might therefore be available in the years to come.

There are still knowledge gaps on potential impacts on the marine environment relating to discharges of oil and chemicals from the offshore industry. Existing monitoring data does not allow to confirm whether or not the observed biological responses are of significance for marine life and ecosystems. There is still a lack of knowledge on the effects of different chemicals and compounds in produced water. Ongoing RBA calculations could potentially generate data that will allow us to target further research and monitoring for a better understanding of possible effects.

1.3 OSPAR Intermediate Assessment 2017 (IA 2017)

The IA2017 comprises information on the pressure on the marine environment from discharges of oil and chemicals in PW. However, the IA2017 does not comprise information on the effects on the marine environment caused by these discharges. Under "Knowledge Gaps" it is indicated that the Risk-Based Approach to the Management of Produced Water Discharges from Offshore Installations (OSPAR Recommendation 2012/5) has not been in operation long enough to indicate whether it is useful for managing impact on the marine environment and that this gap will be addressed as more information becomes available.

1.4 Discharges of oil and chemicals in produced water and from drilling activities 2009 - 2018

Reference is made to the report "Assessment of the OSPAR Report on Discharges, Spills and Emissions from Offshore Installations, 2009–2018, Offshore Oil & gas Industry Series, 2020".

Chemical use & discharge
Since 2001 the use and discharge of chemicals have been covered by a number of OSPAR measures. The total quantity of chemicals used offshore has decreased from 838 111 tonnes in 2009 to 637 797 tonnes in 2018 of which 69 % (wt.) are on the PLONOR[1] list and less than 2 % (wt.) contained substances which are candidates for substitution.

[1] Pose little or no risk to the environment - PLONOR

The total quantity of chemicals discharged into the sea has decreased from 293 402 tonnes in 2009 to 176 721 tonnes in 2018 of which 82% are on the PLONOR list and less than 1 % (wt.) contained substances which are candidates for substitution.

The amount of LCPA substances used has continued to decrease over the 2009-2018 period from 3 929 kg in 2009 to 384 kg in 2018, similarly the amount discharged has decreased from 43 kg in 2009 to 0 kg by 2014.

The discharge of chemicals containing substances that are candidates for substitution decreased from about 1 755 tonnes in 2013 to 1 269 tonnes in 2018, a 28% decrease.

There was a significant increase in the amount used and discharged of inorganic chemicals with an LC50 or EC50 < 1 mg/l as Norway reclassified sodium hypochlorite from a 'Ranking' category in 2015. Denmark similarly reclassified sodium hypochlorite in 2016.

The use of substitution chemicals with a biodegradation of <20% or that meet 2 of 3 PBT criteria has decreased from 11 959 tonnes in 2009 to 7 739 tonnes in 2018, a 36% reduction. Similarly discharge of these substitution chemicals has decreased from 1 753 tonnes to 1 162 tonnes, a 35% reduction.

The use and discharge of Ranking[2] chemicals has decreased by 8% and 10% respectively between 2009 and 2018. The use and discharge of PLONOR chemicals has decreased 29% and 44% respectively over the same period. It is not entirely clear if this is mainly due to an overall reduction in use and discharge or a change in categorisation of chemicals off the PLONOR list.

Discharges of oil to sea

Dispersed oil is discharged into the OSPAR Maritime Area in accordance with OSPAR Recommendation 2001/1 (as amended) which seeks to limit the concentration of dispersed oil in produced and displacement water discharges to no more than 30 mg/l. The Recommendation also called for a reduction in the total oil discharged into the sea in 2006 by 15% compared to the equivalent discharge in the year 2000, which has been achieved. The concentration of dispersed oil is determined in accordance with the OSPAR reference method[3].

The total quantity of dispersed oil discharged with produced and displacement water was 3957 tonnes in 2018, which is a 19% decrease from 2009. This is largely due to decreases in produced water volumes being discharged as installations produce less fluids while dispersed oil concentrations remain steady.

The quality of produced water has remained largely steady from 2009 to 2018 ranging from an OSPAR average of 12.4mg/l to 13.4mg/l as shown in Figure 2.1.

[2] Ranking chemcials being the combination of inorganic chemcials with LC50 or EC50 greater than 1 mg/l and ranking chemicals, which includes substances ranked according to OSPAR Recommendation 2000/2 and don't fall into another category.

[3] OSPAR Agreement 2005/15 https://www.ospar.org/convention/agreements?q=2005-15&t=32281&a=7458&s=

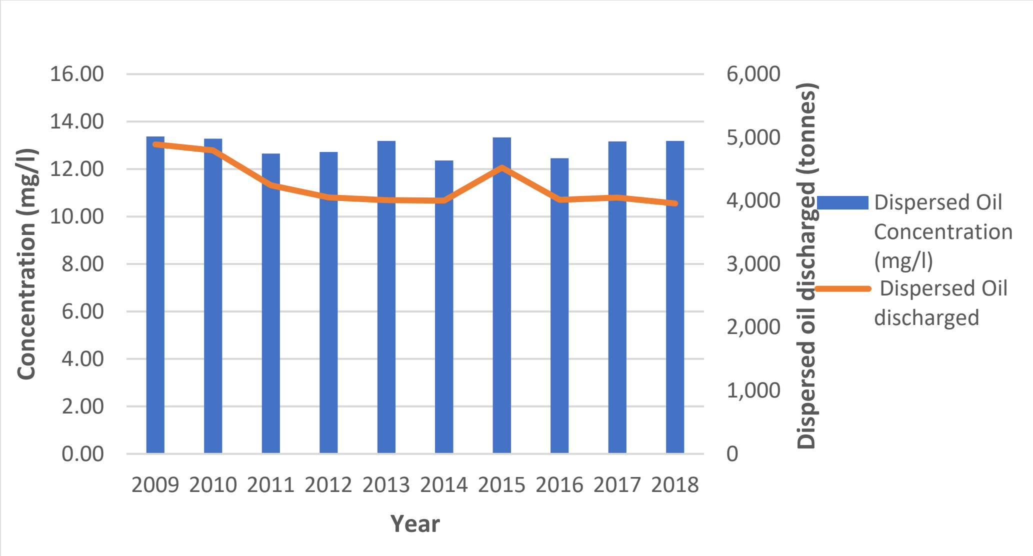

Figure 2.1: Dispersed Oil Discharges

Recommendation 2001/1 sets a performance standard for the discharge of dispersed oil in produced water of 30mg/l calculated as a monthly average. While the majority of installations in the OSPAR Maritime Area meet the performance standard, a number of installations exceed this performance standard on an annual basis. Over the period 2009 – 2018, the total number of installations exceeding the performance standard (PS) has decreased from 31 in 2009, shortly after the new reference method came into effect, down to 20 in 2018 (see Figure 2.2).

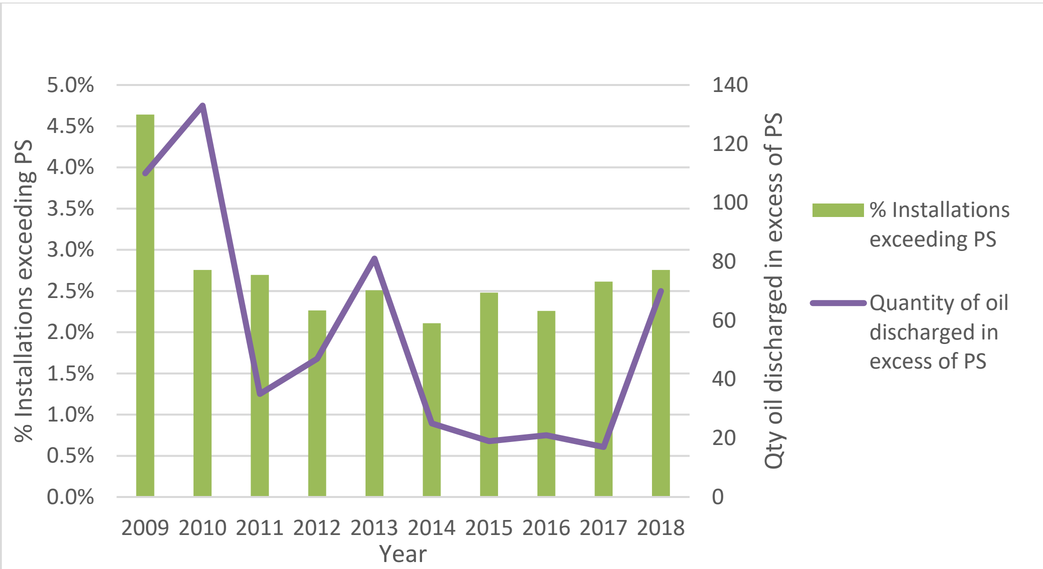

Figure 2.2: Installations exceeding performance standard

The total quantity of hydrocarbons discharged in excess of the performance standards had decreased by 84% over the period 2009-2017, however increased again in 2018 resulting in an overall 36% decrease over the ten-year period. It should be noted that the quantity of dispersed oil discharged in excess of the performance standard equates to less than 2% of the total dispersed oil, discharged in the OSPAR region.

Installations exceeding the performance standard tend to vary from year to year and are mainly as a result of a change in operations, e.g. new wells coming online, malfunctions in separating equipment. Contracting Parties with installations exceeding the performance standard of 30 mg/l on an annual basis have reported the reasons for exceeding the performance standard as well as plans for improvements. In cases where exceedances occur, Contracting Parties take steps to ensure a return to compliance of such installations.

While part of the decrease will be attributable to the change in analytical method, part of the decrease is likely to be as a result of improvements in performance by some installations. It should also be noted that of the 20 installations discharging in excess of 30mg/l during 2018, only 4 installations discharge greater than 2 tonnes of dispersed oil during the year and over 90% of the oil discharged in excess of the performance standard is from just 5 of the 20 installations.¨

Contracting Parties also report the dissolved oil content (as represented by BTEX[4] components) in produced water and displacement water discharges. OSPAR does not regulate for these as they rapidly biodegrade in seawater once discharged. The total quantity of BTEX discharged has remained largely the same over the ten-year period with an average of approx. 4 800 tonnes discharged annually. It should be noted however that there is a large uncertainty in the BTEX analysis due to the infrequent sampling frequency (bi-annual) by most Contracting Parties.

1.5 Risk Based Approach

Through the introduction of the Risk Based Approach (RBA) (OSPAR Recommendation 2012/5) the environmental risk of discharges of produced water are calculated for all installations discharging produced water to the OSPAR maritime area. The purpose of RBA is to assess the environmental risk (e.g. expressed as PEC/PNEC) posed by discharges of oil and other substances with produced water, with the aim of finding appropriate measures to reduce the risk to levels, where the calculations show it is not adequately controlled. Risk assessments on a substance level can help identifying substances aiming for risk reduction and for further investigations of possible biological impacts on marine biota. The risk assessment step will not in itself provide information on the actual impacts on marine biota, but the recommendation includes a step of performing environmental monitoring in order to detect changes in the receiving environment and to verify the impact hypothesis.

Contracting Parties have from 2013 reported annually to the OIC on the progress of the implementation of the RBA method and by 2018 RBA calculations have been made for all offshore oil & gas installations with discharge of produced water in the OSPAR maritime area. The objective being that by 2020 all offshore installations with produced water discharges in the OSPAR maritime area should have been assessed to determine the level of the risk with the aim of, where appropriate, identify measures to be taken to reduce the risk posed by the substances contributing most to the total risk. OIC 2020 will include a discussion of the effectiveness of RBA. The OIC Expert Assessment Panel (2020 draft) reports:

To date, of the 234 installations still included within the RBA process, 218 have been assessed, with 50% of installations determined to have their discharge adequately controlled, 19% requiring further action to be taken and the remainder still awaiting the outcome of an assessment.

The OSPAR RBA guidelines prescribe that the risk of PW can be characterised based on Whole Effluent Toxicity (WET) testing of the PW, or by a Substance-Based (SB) approach including the individual substances identified in the PW, considering the exposure and the sensitivity of the receiving marine environment. Alternatively, a combination of these approaches is to be used to assess the risk.

The first step in the RBA calculation can be done either by using simple dilution factors or by 3-dimensional fate modelling using a dispersion model that take into consideration the hydrography, currents, temperature etc. of the sea. The fate modelling also considers the physical properties either provided (for production chemicals) or defined within the model (for the naturally occurring components) such as biodegradation rate and density. This stage of the process calculates the predicted environmental concentration (PEC) of all the components of the release. The simulation runs with a continuous release over a standardized period of e.g. 30 days.

The following is based on the report Risk Based Approach to Produced Water Management, EIF Calculations Tyra 2016, IRIS report – 2017/229, Revision no: 01. January 9, 2018 by Lyng and Berry:

When using the DREAM-EIF fate modelling, a concentration field for each release is generated throughout the standardized 30 days modelling period. Following the fates modelling, a risk map is then generated by comparing the PEC with the PNEC for the components in the release. The PEC/PNEC ratios are combined based on species sensitivity

[4] BTEX = Benzene, Toluene, Ethylbenzene and isomers of Xylene.

distributions (SSDs) to estimate the Potentially Affected Fraction of species (PAF) and assessing overall risk by multi-substance PAF (msPAF) which combines the PAF for all components in the discharge.

The results of the RBA calculation can be expressed as Environmental Impact Factor (EIF) as originally described by the Johnsen et al. (2000). The Environmental Impact Factor (EIF) concept is illustrated in Figure 2.3. The model calculates EIF, where EIF=1 represents a volume of water 100x100x10m in which the risk (msPAF) exceeds 5%, or where PEC/PNEC ratios are ≥ 1.

For each discharge point, risk maps are generated, illustrating the risk of the discharge in terms of PEC/PNEC ratio. An example of a risk map can be seen in Figure 2.4.

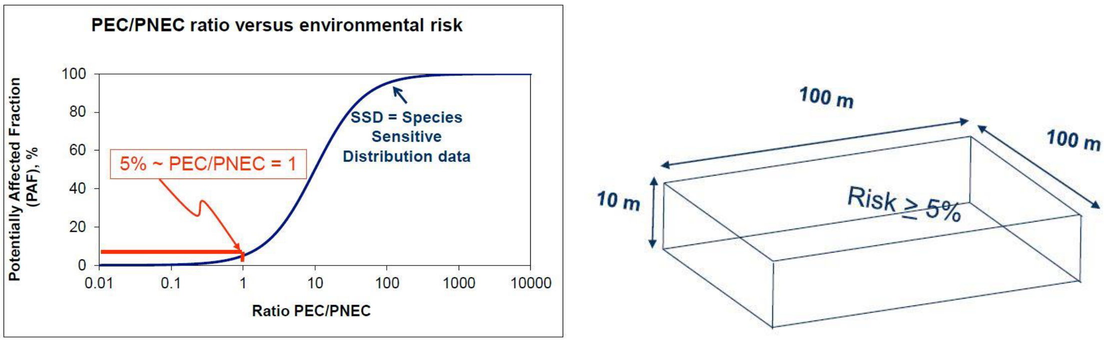

Figure 2.3: Illustration of the EIF concept

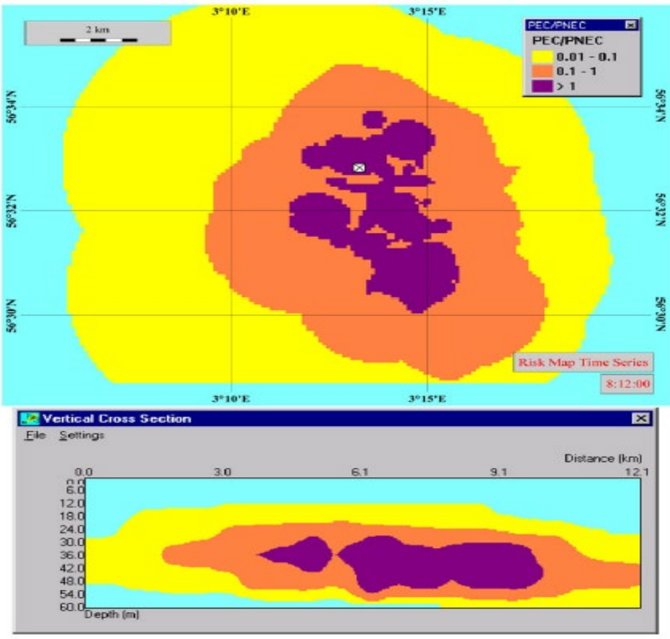

Figure 2.4: Example of a calculated risk map, coloured after the PEC/PNEC value of the sum of PW constituents. Horizontal view in upper panel and vertical view in lower panel (Miljø- og fødevareministeriet, 2018).

The results of these calculations can also be seen on a component-based level, and the contribution to risk for each of the components in the discharge can be calculated in the risk modelling. This contribution to risk can be illustrated in a pie chart generated for each discharge (Figure 2.5). For each simulation, both a time-averaged EIF and a maximum instantaneous EIF can be generated. The first represents an average over the 30-day period, while the second represents the maximum risk recorded at a single time point during the 30-day simulation period.

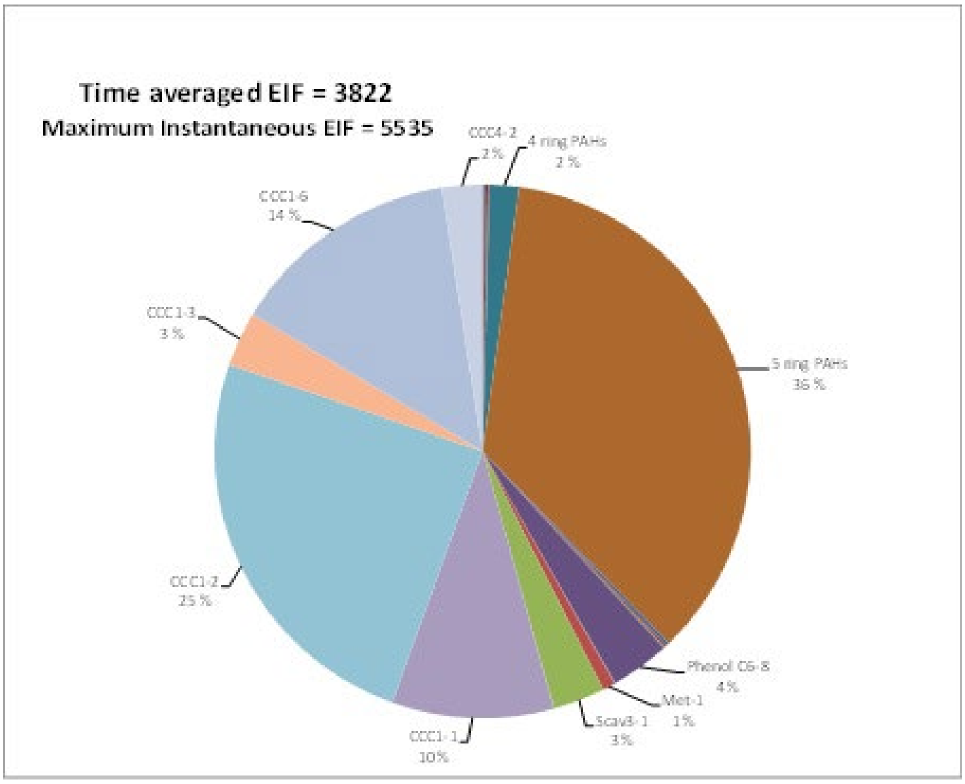

Figure 2.5: Example of the contribution to risk from the different components of the discharge with indication of both time-averaged risk and maximum instantaneous risk both expressed by EIF (CCC = Corrosion Control Chemical, Scav = H_2S Scavenger). Ref. Miljø- og fødevareministeriet (2018)

If a WET based approach is applied, using WET data, the risk can also be expressed as EIFs, or it can be expressed as the distance to the discharge point where the sum of PEC/PNEC ratios is greater than 1.

Risk levels of PW discharges in the OSPAR area have been reported through the yearly reporting to the OIC. Due to differences in the available information on added chemicals, different discharge factors, dilution and dispersion models, the results from installations within, and especially between the Contracting Parties cannot be compared. Nevertheless, a main finding is that some types of offshore chemicals are major contributors to the risk posed by PW discharges. The extent of the contribution may be overestimated due to the scarcity of long-term toxicity data and the use of large assessment factors, but for some production chemicals, their toxicity is inherent to their desired function. For several installations, discharges of corrosion inhibitors and biocides, not surprisingly, are major contributors to risk. Corrosion inhibitors may include a range of inorganic and organic substances.

By 2018 several installations with discharges of PW are considered to have an adequately controlled risk, meaning no increased risk level beyond 500 metres from the installation or an EIF below 10. These acceptance levels are not decided and agreed upon by OSPAR but are used by several Contracting Parties according to national guidance.

The RBA work will continue, and further development and refinement of the methods used will be made. Since the 2012/5 recommendation allows for different approaches and methods it is difficult comparing risk levels also in the future. The main purpose is however to have risk management tools to identify the right measures for site specific risk reductions.

Linking the estimated risk levels to possible impacts in the receiving environment is a step that has not yet been addressed.

Available information and data in reports on laboratory analyses and monitoring programs on impacts of oil and chemicals from the offshore industry on the marine environment.

This part of the report presents information and data from recent reports on Water Column Monitoring conducted on Norway's Continental Shelf and from reports on Seabed Monitoring Programs conducted around offshore oil & gas installations on Norway's, United Kingdom's and Denmark's continental shelfs. It presents extracts from the different monitoring reports. Only editorial changes have been made, e.g. to, where relevant, avoid repetition of similar text in the different reports or to clarify the language.

1.6 Water Column Monitoring (WCM)

This section presents results of the most recent Water Columns Monitoring Program carried out on the Norwegian Continental Shelf. So far, Norway is the only OSPAR country that on a regular basis has carried out such monitoring programs around offshore oil & gas installations.

1.6.1 Norway 2017

The Norwegian Oil & Gas Association commissioned NORCE (which now includes the previous International Research Institute of Stavanger, IRIS), the Norwegian Institute for Water Research (NIVA), the Institute of Marine Research (IMR) and SINTEF to carry out a Water Column Monitoring program in three different regions of the North Sea: Tampen area, Central North Sea, and Egersund Bank (reference area). Additionally, focus was on studying the water column conditions around the Statfjord A and B platforms (Tampen area).

The following text is extracted from the Pampanin et al. (2019) report "Water Column Monitoring 2017, Environmental monitoring of petroleum activities on the Norwegian continental shelf 2017, September 15, 2019 (report no.: NORCE Environment 007-2019)".

Monitoring program and method
The WCM 2017 was carried out in three different regions of the North Sea: Tampen area, Central North Sea, and Egersund Bank (reference area). Additionally, focus was on studying the water column conditions around the Statfjord A and B platforms (Tampen area) – see Figure 3.1 and Figure 3.2.

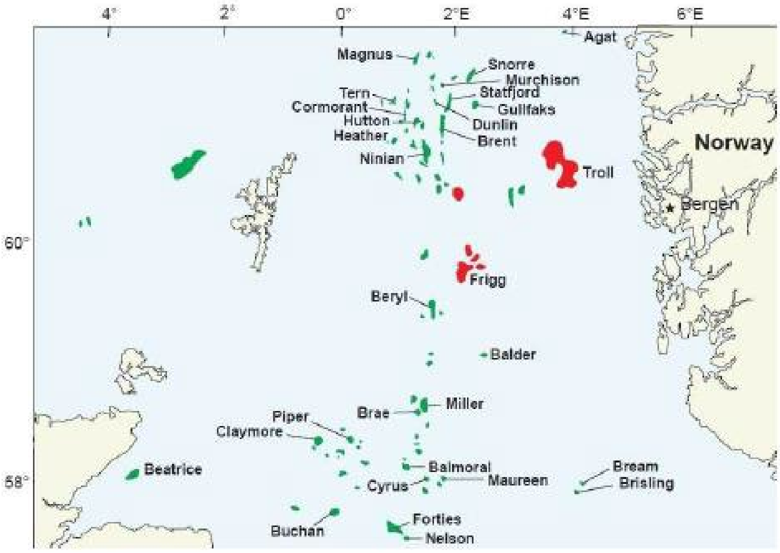

Figure 3.1: Statfjord oil field relative location in comparison with Norway and UK coastlines

Figure 3.2: Statfjord oil field relative position in comparison with the Norwegian coastline

The WCM monitoring priorities in 2017 were to determine:

- *potential effects of oil and gas related discharges in mussels caged around the Statfjord A and B platforms (WP1)*
- *potential effects of oil and gas related discharges in wild fish caught around the Statfjord A and B platforms (WP2)*
- *potential effects of oil and gas related discharges in wild fish caught in three regions of the North Sea (WP3)*
- *a preliminary study to evaluate the potential use of zooplankton as a monitoring tool for studying the effect of oil and gas related discharges (zooplankton-based monitoring) (WP4)*

In addition, priority was given to a research study on method development for DNA adducts in fish (WP5).

The 2017 program was designed to evaluate effects of oil and gas activities near field (i.e. around selected platforms) and at regional scale, combining two programs previously called "effect monitoring" and "condition monitoring".

Chemical and biological results are described in this report and discussed in relation to the stations distance from a PW discharge point (i.e. Statfjord A and B), or in relation to regions (i.e. Tampen, Central North Sea, Egersund Bank). In addition, biological marker results were integrated using the Integrative Biological Response (IBR) index. This data treatment was developed to integrate biochemical, genotoxic and histochemical biomarkers by Beliaeff and Burgeot (2002). The method is based on the relative differences between biomarkers in each given data set and it has been applied in previous WCM programs.

*For the first time the 'biomarker bridges' approach was applied to enhance the interpretation of the biological marker (Sanni et al., 2017a, b, c). It has been possible to utilize a considerable part of the survey data to make assessments of interest, such as indications about the obtained biomarker responses compared to discharges, to expected impacts and risk*s

With regard to the caged mussel study, it is important to note the shift in mussel species distribution among Norwegian populations. In comparison with previous surveys, there has been a reduction (-6%) in M. edulis and an increase in hybrid species. Mussels were purchased from a farm in Trondheimsfjorden (Norway); this source has been used previously for the WCM program. Since different genera may have differing capabilities to accumulate and respond to pollutants, this issue will need to be addressed in future WCM programs.[5]

[5] Comment to text: Of relevance at least for the Mytilus species hybrids, Blackmore & Wang (2003) studied accumulation of heavy metals in across Mytilus species and found similar accumulation rates. See section 3.3.2 "Mussels".

Results

The sum of PAH concentrations in mussel tissues showed higher body burden concentrations in organisms that were caged closest to both Statfjord A and B platforms. However, these values were lower than those from previous surveys. For PAH accumulation, naphthalenes were the most abundant followed by phenanthrenes and dibenzothiophenes. The source of the PAHs has been identified as petroleum, as in previous surveys at Gullfaks C, Troll C and Ekofisk.

Regarding the biological effect parameters, some highlighted a stress condition present in mussels caged at Statfjord A and B. When comparing results against ICES assessment criteria, mussels appear to be in stress conditions, but compensating, as confirmed by the physiological level measurements (stress on stress and condition index) and their ability to maintain reproductive development (e.g. spawning status). However, signs of more severe stress conditions were recorded in mussels caged 500 m from Statfjord A, by means of lysosomal membrane stability and micronucleus (MN) frequency in haemocytes. In particular, at 4 stations close to the platform, MN frequency values were above the elevated response (ER) limit suggested by ICES, showing a clear sign of the presence of contaminants with genotoxicity potential.

Data integration using IBR/n confirmed that stressed organisms were compensating, by showing IBR/n values within the range of the two reference stations. Two stations located at 500 m from Statfjord A had the highest IBR/n values, indicating a more severe level of stress.

Regarding analyses in wild caught fish, four areas were considered: Statfjord, Tampen, Central North Sea and Egersund bank (as a reference). Unfortunately, liver samples from Statfjord, planned to be held at -80 °C prior to analysis, appeared to have suffered a thawing incident, which may have occurred during the transport to the laboratory. DNA adduct analysis was still possible. However, the EROD, Cyp1A and gene expression results were below detection limits and could not be considered for further discussion in this study.

PAH metabolites were significantly higher in cod collected at Statfjord (i.e. 2,3-ring PAHs and 5-ring PAHs), and in whiting sampled at Tampen area (i.e. 4-ring PAHs) compared to the reference site. The increased levels of PAHs in the water column at Tampen and Statfjord shown in soft tissues of deployed mussel was less evident in fish. Nevertheless, genotoxic effects were clear in fish, as revealed by both DNA adduct and comet assay results. DNA adduct levels were higher at Tampen and Statfjord compared to the reference area. In addition, DNA adduct levels were significantly different between species at Tampen, with higher levels for haddock and saithe, compared to the refence area. DNA adduct levels were also significantly different among fish species collected from Statfjord A, with higher levels for haddock, whiting and ling. DNA adducts were also analysed in the intestines of a subset of samples and higher levels of DNA adducts compared with fish from the reference area were found. Part of the difference could, however, be explained by age differences among the fish.

Levels of DNA adducts from haddock livers at Tampen were higher than those reported in the condition monitoring programs from 2005-2011 and levels were above environmental assessment criteria (EAC) suggested by ICES at Tampen and at the Statfjord A field in all 6 investigated species. In addition, adduct levels in intestine tissue from these species were also above EAC in samples taken from the Statfjord A field.

A significant inhibition in acetylcholine esterase (AChE) activity were observed in ling from Statfjord and cod from Statfjord and Tampen, compared with the Egersund Bank, although not found for whiting and saithe. Inhibition in AChE activity may indicate possible exposure to neurotoxic contaminants. ICES assessment criteria have been developed for AChE in a few marine fish, including dab, flounder, red mullet and eelpout, but not for the fish species used in this study.

1.7 Studies on Produced Water

This section presents results of studies on the ecotoxicology of produced water. It should be noted that exposure to produced water in the sea will not be constant as it is in laboratory trials. In the field the exposure of organisms will fluctuate because of varying (daily-to-weekly) rates of PW discharge, and varying (hourly-to-monthly) currents that will affect the dilution rate of produced water. Other processes influencing exposure include environmental degradation of PW components, sedimentation and organisms' activity such as fish's avoidance of the PW plume, and shell closure in bivalves. Phyto- and zooplankton with limited self-movement abilities are subject to currents and time-varying exposure, typically with short-lived "high" exposure concentration when meeting the PW plume close to the discharge points followed by gradually decreasing PW concentration along with PW dispersion and dilution. Therefore, controlled constant laboratory exposures cannot mimic *in situ* PW conditions but provide a valuable basis for understanding the cocktail effect from produced water.

1.7.1 Norway 2012

The Norwegian Oil Industry Association (OLF), the Ministry of Petroleum and Energy and the Ministry of the Environment together funded the program "Long-term effects of discharges to sea from petroleum-related activity", which was a sub-program of the Research Council of Norway's Oceans and Coastal Areas program. The sub-program started as a separate research program in 2002 named "PROOF" and later continued as the sub-programme "Oceans and Coastal Areas – PROOFNY".

In 2012 PROOFNY concluded with the report "Long-term effects of discharges to sea from petroleum-related activities, The results of ten years' research", Research Council of Norway 2012. The following text is an extract from this report mainly focusing on methods, results and conclusions in regard to the impacts of discharges of produced water. For references in the text, reference is made to the reference list in the original report.

Objective and content

The objective of PROOFNY is to increase knowledge about how discharges from petroleum related activities can impact on the marine environment in the long term. By this is meant effects that span more than a generation or that lead to a long-term negative change in communities or ecosystems. Studying the connection between effects on individuals and effects on populations and ecosystems has been a consistent challenge. PROOFNY has prioritised the following issues:

- *Long-term effects of operational discharges from production and drilling*
- *Arctic organisms' sensitivity to discharges of oil and chemicals from the petroleum industry, with particular emphasis on ice-covered waters*
- *The development of new and improved methods for environmental monitoring and early warning of effects*
- *The effects of acute discharges of oil, with particular emphasis on the water column, shore zone and ice-filled waters.*

Until 2011, PROOFNY comprised 65 projects and resulted in around 110 publications and reports. The bulk of the projects have concerned operational discharges, primarily of produced water. Monitoring and surveys have shown that such discharges are very quickly diluted to concentrations that are below the limit for biological effects. It has therefore been a goal to develop methods that can detect and quantify low concentrations of discharged substances in water and organisms, and methods for detecting possible effects of such concentrations.

Measuring produced water components in water and organism

It is necessary to use advanced chemical analysis methods in order to determine the content of chemical substances in reasonably good detail. PAHs and alkylphenols have received most attention because of their prevalence and known toxic effects. Produced water is quickly diluted after discharge, so that the levels of PAHs and alkylphenols often go from ng/l to pg/l in sea water. Methods have been developed through the use of passive sampling devices (SPMD, POCIS) that absorb and enrich substances from the water masses over time to levels that it is possible to measure (Boitsov et al. 2004, 2007, Harman et al. 2008a, b, 2009, 2010, 2011). One of the important conclusions from these projects is that different types of passive sampling devices must be used for non-polar substances such as PAHs and for polar substances such as alkylphenols.

Many different methods have been developed over the years for analysing PAHs in biological material. The methods, which often make use of chromatography (GC/MS or HPLC), are selective and sufficiently sensitive to calculate the content of individual components in, for example, the muscle and livers of fish. A method has been developed in PROOFNY for the measurement of alkylphenols in the biological material. It includes extraction with dichloromethane, *the removal of fat from the extracts, derivatisation and analysis on GC/MS (Meier et al. 2005). This method enables highly sensitive measurements to be made of the meta-substituted and para-substituted alkylphenols, but it is less suitable for the ortho-substituted alkylphenols (see, for example, Boitsov et al. 2007).*

Fish have a great ability to break down and excrete substances such as PAHs and alkylphenols, but products of the biodegradation process can be detected in bile fluid. As part of PROOFNY, GC/MS-based methods have been further developed to analyse bile metabolites, so that it is now also possible to detect metabolites of PAHs and alkylphenols in wild fish (Jonsson et al. 2008a, b, Brooks et al. 2004, 2009, Harman et al. 2009a, Sundt et al. 2009a, b). The methods have been used both in experimental studies and in the monitoring of areas around installations.

A few alternative methods to advanced and expensive chemical analyses of bile metabolites have also been tested. The principle is based on creating electrochemical sensors that can measure PAH metabolites with affinity to a DNA coating (Lucarelli et al. 2003, Bagni et al. 2005). A corresponding electronic sensor for the registration of alkylphenol metabolites is also under development (Bulukin et al. 2006). The goal is to make it possible to use such methods for a quick and cheap test that shows whether a sample contains metabolites of PAHs and alkylphenols. Some methodological challenges concerning selectivity and sensitivity remain to be solved.

Several studies have been carried out to investigate what determines the absorption, conversion and excretion in fish of substances from produced water. Experiments have been conducted with substances administered via both sea water and food. A strong connection has been found between the level of PAHs and alkylphenols in sea water, the substances' affinity to fat and the levels of bile metabolites in cod (Grung et al. 2009). The connection was less clear for volatile compounds and for PAHs and alkylphenols in food. In an experiment with radioactively marked alkylphenols, it was found that the concentration in bile was ten times higher when the alkylphenols were administered in water than when they were administered in food (Sundt et al. 2009a). Several studies have shown that alkylphenols are easily absorbed by fish, but also that they are excreted via bile over a period of hours or a few days. Adult fish excrete PAHs effectively through bile over a period of days to weeks. Cod eggs, larvae and fry also effectively absorb alkylphenols from produced water (Meier et al. 2010). It has been shown that the earliest life stages (eggs and larvae) have less capacity to metabolise and excrete the short chain alkylphenols than juvenile and adult fish.

Biological effects of produced water

Concern has been greatest about the effects on the reproductive ability of fish, particularly the effects of alkylphenols. Alkylphenols have been shown to have oestrogen-like effects on fish that, in turn, can manifest themselves in interference with gonad development and the production of eggs and sperm. Some PROOFNY projects have emphasised effects of this kind. Tollefsen et al. (2007) and Tollefsen and Nilsen (2008) found that, for rainbow trout, alkylphenols bonded effectively with proteins that normally bind steroids, and that alkylphenols and other substances in produced water may therefore have a sex hormone mimicking effect, even at levels as low as realistic concentrations in sea water. Tollefsen et al. (2011) showed that complex mixtures of oil-related substances affected the reproductive physiology of cod, while typical health indicators such as condition index and relative gonad and liver weight were not affected. Several other surveys support these results, showing that substances in produced water can interfere with sexual development and reproduction in fish (Meier 2007, Tollefsen et al. 2007, Thomas et al. 2009, Meier et al. 2011, Sundt & Bjorkblom 2011). The concentrations that have produced effects are normally only found in water masses nearer than a few kilometres from discharge sites. Meier et al. (2010) concluded that extensive and long-term reproductive effects of produced water on fish are not very probable.

PROOFNY has shown that produced water can also have a number of other effects. Cod that were given food with alkylphenols showed clear signs of oxidative stress after one week (Hasselberg et al. 2004a, b). There were also signs that alkylphenols inhibited CYP1A and CYP3A enzyme activity in male fish after four weeks. This enzyme system is the fish's first line of defence against alien substances. In other projects, it has been found that produced water can also stimulate the same enzyme activity in cod (for example Abrahamson 2008, Meier et al. 2010, Jonsson & Björkblom 2011, Sundt et al. 2011). The fact that substances in produced water can both inhibit and stimulate the same enzyme system makes it difficult to interpret responses found in the environmental monitoring of produced water. Oxidative stress and cell death have been found in experiments with liver cells from rainbow trout exposed to water-dissolved fractions and droplets of oil from 10 different types of produced water (Farmen et al. 2010). However, the levels required to cause *oxidative stress were several orders of magnitude higher than typical levels in the sea around discharge sites. Tollefsen et al. (2008) concluded that liver cell death in rainbow trout caused by alkylphenols was probably due to the impact on the cells' metabolism. Holth et al. (2010, 2011) found that the long-term exposure of cod to a simulation of produced water containing phenol, alkylphenols and PAHs resulted in changes in the genes that govern detoxification, the immune system, cells' selfdestruction (apoptosis) and oxidative stress. Neither survival nor general health parameters such as condition index, relative gonad and liver weight and haematocrit were affected. Meier et al. (2010) found that newly hatched cod larvae exposed to 0.1% and 1% produced water died as a result of losing their ability to absorb nutrition. Genetic damage in the form of an increase in DNA adducts and the occurrence of micronuclei have been found in experiments on cod exposed to oil and alkylphenols (Holth et al. 2009) and in wild haddock from the Tampen area in the North Sea, where petroleum-related activity is very high (Grøsvik et al. 2010, Balk et al. 2011). Alkylphenols in food have also been found to increase the proportion of saturated fatty acids and reduce the proportion of polyunsaturated fatty acids in the livers of cod (Meier et al. 2007). Grøsvik et al. (unpublished) found a corresponding change in the fatty acid composition of wild-caught haddock from the Tampen area.*

PROOFNY has also documented effects on invertebrates of PAHs and other oil components that are common in produced water. Baussant et al. (2011) confirmed previous findings by Lowe and Pipe (1987) that dispersed oil can prevent egg development in mussels and actually lead to the eggs being broken down for other metabolic purposes. Baussant et al. (2011) found that oil also caused DNA damage in mussel larvae after hatching.

The PROOFNY projects have thus shown that produced water can give rise to a number of effects in fish and other marine animals. Several of the effects are natural reactions to chemical stress and should not have negative effects as long as the capacity to withstand such stress is not exceeded. Other effects show more fundamental biological changes, such as cell death, genetic change, DNA damage, a change in fatty acid composition and interference with reproduction. It is a common denominator for all these surveys that the effects were detected at a dilution of produced water of 0.1 – 1% or higher. This is a dilution that is found very close to the discharge source. Available measurement results from fields have usually also given indications that the effects are local. Effects have also been found in haddock from the Tampen area caught at greater distances from the discharge sources, but these are probably persistent effects of local exposure, not effects of low exposure in a wider area.

One important goal of PROOFNY has been to increase our understanding of the mechanisms behind the effects found. This has motivated surveys of what are known as '-omics' responses, i.e. how the whole pattern of important groups of substances in cells and tissue is affected. They can be genes (genomes), RNA (transcription), proteins (proteomes) or the total content of certain metabolites (metabolomes). While the development of '-omics' methods is still in its infancy and we have little experience of interpreting the patterns, it is expected that this type of mapping could increase our understanding of effect mechanisms at the individual level and lead to the identification of 'signal' molecules or molecule patterns that are both sensitive and regulate important biological functions. Thus, '-omics' patterns have a clear potential in relation to monitoring effects on natural organisms around discharge sites. Projects under PROOFNY (Bohne-Kjersem et al. 2009, 2010, Karlsen et al. 2011, Nilsen et al. 2011a, b) have shown that crude oil, 'artificial' produced water and alkylphenols can lead to clear changes in the protein profile of eggs, larvae and juveniles of cod. These are proteins that regulate the immune system, fertility, skeletal and muscular development, eye development, fatty acid conversion, cell mobility, apoptosis and other vital functions. In an ongoing project (Karlsen et al. 2011), the aim is to increase our understanding of cod's genome responses to produced water by linking data from proteome and transcriptome analyses to ongoing work on gene sequencing for cod (www.codgenome.no).

In order to understand how produced water can influence the pelagic production system, it is important to be aware of the effects on zooplankton. So far, the methods used to study this have been unreliable. Several PROOFNY projects have studied gene transcription and other molecular responses in Calanus finmarchicus and a closely related species of copepod in a project covering several generations (Hansen et al. 2007, 2008a,b, 2009, 2010, 2011). They have found that dispersed oil, the PAH compound naphthalene and copper can modify genes involved in processes such as nutrient absorption, shell replacement, the storage and conversion of fat, protein and amino acid metabolism, as well as defence mechanisms against toxicity and oxidative stress. The method therefore has a clear potential in relation to the monitoring of effects around produced water discharge sites.

Conclusions

PROOFNY has shown that components of produced water can cause a number of negative effects that have that consequences for the health, functions and reproduction of individual fish and invertebrate animals. Particular emphasis has been placed on possible endocrine effects, but other types of effects, such as genetic damage, oxidative stress, growth and reproduction, have also been found.

New and improved methods have also been developed for measuring biological responses that are both sensitive and of fundamental importance to the affected organisms. In particular, surveys of molecular biological patterns of, for example, genes, proteins and other vital groups of substances appear to be capable of combining sensitivity with high ecological relevance. The development of these methods is still in its infancy and it has not been sufficiently clarified how useful they can be, for example in environmental monitoring.

However, the ecological importance of the discharges will remain unclarified as long as the effects it has been possible to measure cannot be linked to consequences for populations and communities. The main impression from PROOFNY is nonetheless that the potential for environmental harm is generally moderate, and the concentrations that have produced effects do not normally occur more than around one kilometre from the discharge points. This accord well with both monitoring results and the risk assessments that have been carried out. It is not possible, however, to rule out the risk that weak effects on individual species may have cumulative ecological effects, even though the probability of this is low.

Knowledge gain, effects in the Arctic

In comparative studies, differences in vulnerability have been found between Arctic and temperate species in relation to both discharges of produced water and drilling waste. The differences have been small, however, and they go in both directions. There is nothing in the results to indicate that marine organisms that are important in Arctic and sub-Arctic communities are more vulnerable to discharges than similar organisms elsewhere on the continental shelf. Rather effect-producing processes appear to progress more slowly under sub-Arctic conditions. This also applies to the biodegradation of oil. However, individual species' vulnerability is only one factor that determines whether the Arctic ecosystem can handle discharges in the same way as temperate ecosystems. Large-scale factors such as climate, ecological seasonal variation, spatial distribution of populations and communities and discharge conditions will, as far we can see, dominate in relation to the overall consequences of operational and unintended discharges.

1.7.2 Denmark 2015

In 2015 the Danish Environmental Protection Agency commissioned DHI to review relevant methods of investigation and tools for monitoring and assessment of environmental effects in the water column of pollutants from the offshore oil and gas sector in the North Sea. The review was published in the Rasmussen and Pedersen report “Existing studies and measurements of environmental effects in open waters”, December 2015 (OIC 16/8/2 Rev.1 Add.1).

Objective of the report

The report summarised public available information on studies and monitoring of environmental effects in open waters caused by discharges of pollutants into the environment. This includes information on monitoring around outlets from offshore activities such as the oil and gas industry as well as from activities by other industries. Focus is primarily on discharges of produced water from oil and gas platforms.

Naturally occurring components in produced water

The alkylphenols (AP) are of immediate highest concern with Risk Characterization Ratio-ranges of up to 2000. These substances together with the naphthenic acids are also known or at least suspected to be xeno-estrogens. High RCR ranges are also noted for the BTEX-substances (Benzene, Toluene, Ethylbenzene, Xylenes). However, these substances are expected to dissipate quickly from the water column due to evaporation. The PAHs may also have severe effects such as carcinogenicity, DNA damage, embryo-toxicity, growth, oxidative stress - on the water column organism. Several of the heavy metals, which are found at elevated concentrations in the PW have a high potential for *bioaccumulation and are systemic toxicants. The hydrocarbons do also exhibit narcotic effects in both crustaceans, algae and fish.*

Added chemicals in produced water

Chemicals added for different purposes during processing or separation of produced oil and gas will end up in the produced water and contribute to the overall toxicity of the PW. A huge number of different offshore chemicals are applied, and the toxicity of these chemicals may differ up to several orders of magnitude.

Whole Effluent Toxicity (WET) tests

Several toxicity tests on the whole effluent of PW have been reported. The overview below is based on the review presented in ref. /25/.

From 108 results from WET testing of produced water with 22 species of marine and coastal animals, it was found that:

- *88.9% of the results gave a LC50 > 10,000 ppm (corresponding to a dilution of approximately 100 or less):*
- *11.1% of the results gave a LC50: 1000-<10000 ppm (corresponding to a dilution between 100-1000):*

In ecotoxicity studies of PW from the Norwegian sector in the North Sea, it was found that:

- *0-35.7% of the test organisms (Artemia salina=brine shrimp) died in a 24hr test where the test organisms were exposed to undiluted PW*
- *EC50 (Skeletonema costatum): 4.5-67.6% produced water, i.e. 50% of the test organism were affected in test solutions with a PW concentration between 4.5 and 67.6% (corresponding to a dilution factor between 1.55 - 226)*
- *EC50 (Photobacterium phosphoreum): 5.7-19.2% of PW (corresponding to a dilution factor between 5-18)*

In WET tests of PW from the North Sea platforms carried out at DHI where bacteria, algae and crustaceans were used as test organisms, it was found that algae in general are the most sensitive species. Bacteria were the most sensitive species in a few non-toxic samples. This is in agreement with the above-mentioned studies (ref /25/).

From above, it can be concluded that acute effects of PW in the vicinity of the platform can be expected, but at distances ensuring a dilution above ca. 1000, acute effects from PW are expected to be limited.

Long-term studies on effects of marine organism exposed to PW

Several studies on the long-term exposure of marine organisms to produced water and crude oil are available:

Meier et al. (2010) (ref. /16/) *exposed embryos and juvenile Atlantic cod to a dilution series of PW from the Ekofisk oil platform. The concentration of PW in the test samples were 0.01%; 0.1% and 1% - corresponding to dilutions of 10000, 1000, 100 respectively.*

AP and PAH concentrations were measured in the undiluted PW. The concentration of AP in the PW was approximately 13 mg/L of which phenol and methylphenol contributed with 93%. The concentration of 2- and 3-ring aromatic hydrocarbons (NPD: Naphthalene, Phenanthrene, Dibenzothiophene) was approximately 0.5 mg/L, and the concentration of PAH (acenaphthylene, acenaphthene, fluorene, anthracene, phenanthrene, c1-phenanthrene, pyrene, benz(a)anthracene, perylene, dibenz(a,h)anthracene) was approximately 50 µg/L). The concentration of the highly volatile PAHs was low presumably due to the preceding aeration of PW to remove the toxic H2S.

They found an increased AP concentration in organisms exposed to the higher PW concentrations and the concentration was dependent on developmental stage of the organisms. Furthermore, they found that the exposure did not have an effect on the embryo survival and hatching success of embryos. However, post hatch mortality increased after exposure to 1% PW. This observed effect was linked to an increase in jaw deformations amongst *exposed organisms resulting in a reduced food intake. CYP1A[6] and Vitellogenin[7] (Vtg) concentrations were also elevated in juveniles when exposed to 1% PW (NOEC is therefore set as 0.1% PW and LOEC between 0.1% and 1%).*

Sundt and Björkholm (2011) (ref. /20/) *exposed 2 year old Atlantic cod to PW from an oil production platform (0.066% PW (PAH: 0.17 µg/L) and 0.2%PW (PAH: 0.57µg/L)) for 12 weeks. The presence of phenol and C1–C9 alkylated phenols in the PW was measured to be 3.9 and 5.7 mg/L, respectively (no indication on whether this is for the undiluted PW). During the exposure PAH and AP were measured on a weekly basis. Naphthalene and phenanthrene were the dominating PAHs. After exposure significantly increased PAH and AP-metabolite concentrations were found in the bile of the Atlantic cod. Females exposed to 0.2% PW showed significant increase in VtG and a significant decrease in estradiol levels (LOEC = 0.2%, NOEC = 0.066%). No morphological changes were observed.*

Holth et al. (2010) (ref. /13/) *exposed Atlantic cod for 11 months to artificial PW containing APs, PAHs and phenol at high concentrations (PAH 5.4 mg /L; AP 11.4 mg /L) and low concentrations (PAH 0.54 mg /L; AP 1.14 mg /L). Exposure was continuous or 2 weeks pulsed mode for the high concentration. Gross health parameters (condition factor, liver somatic index, gonadosomatic index, and hematocrit), frequency of micronucleated erythrocytes, oxidative stress in whole blood, and survival were not affected. However, a range of toxicologically relevant genes were differentially expressed in the exposed fish compared to the non-exposed fish, including AhR-responsive genes (metabolic activation of aromatic hydrocarbons, e.g. PAH) and genes relevant to immune function, apoptosis (responsible for control and regulation of cell deaths), and oxidative stress (hepcidin, serotransferrin, glutathione peroxidase).*

Brooks et al. (2011) (ref. /3/) *investigated the exposure of mussel Mytilus edulis (5wk) to PW derived from a gas processing plant. Measured concentrations of pollutants (PAH, metal) in mussel showed no difference between exposure groups. Biomarker stress responses were observed at 0.01-0.5% PW and anomalous responses were observed at 1%.*

1.7.3 Norway 2019

An expert group on offshore environmental monitoring appointed by the Norwegian Environment Agency (NEA) did in 2019 compile a broad knowledge summary of the ecotoxicological implications of offshore produced water (PW) discharges, especially viewed in a Barents Sea context.

The following text is extracts from the Beyer et al. (2019) report “Environmental effects of offshore produced water discharges evaluated for the Barents Sea”, NIVA report no. 7391-2019 / Norwegian Environment Agency report M-1370|2019. The report is the only study made available by Contracting Parties directly in connection with the preparation of this assessment report:

Objective of the study

The objective of the study was to make an overview of the research literature that concern environmental effect of offshore PW discharges, with emphasis on issues that are relevant for the Barents Sea and Arctic seas, and particularly regarding Norwegian research studies. The work is an update of the review by Bakke et al. (2013) summarising recent research on operational discharges of PW offshore.

Research on the effects of PW in marine organisms

One effect phenomenon in oil exposed fish that has received much attention in recent years is the development of irreversible cardiac defects and impaired cardiorespiratory function in fish fry after exposure to very low levels of PAH contaminants originating from oil contamination (Incardona et al., 2004; Carls et al., 2008; Dussauze et al., 2014). Controlled laboratory experiments show that the induced cardiac defects impact the individual fitness of fish fry in several critical ways, including reduced swimming performance, prey capture, and prey avoidance, with repercussions for survival and possibly for population recruitment (Incardona et al., 2015). Oil induced cardiotoxicity of developing eggs

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[6] Indicator for the metabolic activation of carcinogenic polycyclic aromatic hydrocarbons (PAHs)

[7] Indicator for xeno-estrogenic effects

and larvae of haddock (M. aeglefinus) was recently studied by The Institute of Marine Research (IMR) in Bergen (Sørhus et al., 2015; Sørhus et al., 2016b; Sørensen et al., 2017; Hansen et al., 2018b). Haddock are believed to be particularly sensitive to oil during early life stages because the egg/embryo surface (chorion) is very sticky and adsorbs dispersed oil droplets (Figure 3.3). This probably leads to a stronger and prolonged interaction between oil and embryo in comparison to species without a sticky chorion, as for example Atlantic cod. Increased amount of oil droplets on the chorion may lower the exposure time sufficiently to cause toxicity, e.g. in a diluting PW plume. Research by IMR suggests that even a short exposure to a high concentration of dispersed oil may continue to affect the haddock embryos even after they have been transferred into non-contaminated water by the carry-over of attached oil droplets as a continued source of exposure (Sørhus et al., 2015). Whether these differences between haddock and Atlantic cod can make the haddock more sensitive/vulnerable to oil contamination, and to develop adverse cardiac conditions after oil exposure, remains to be seen.

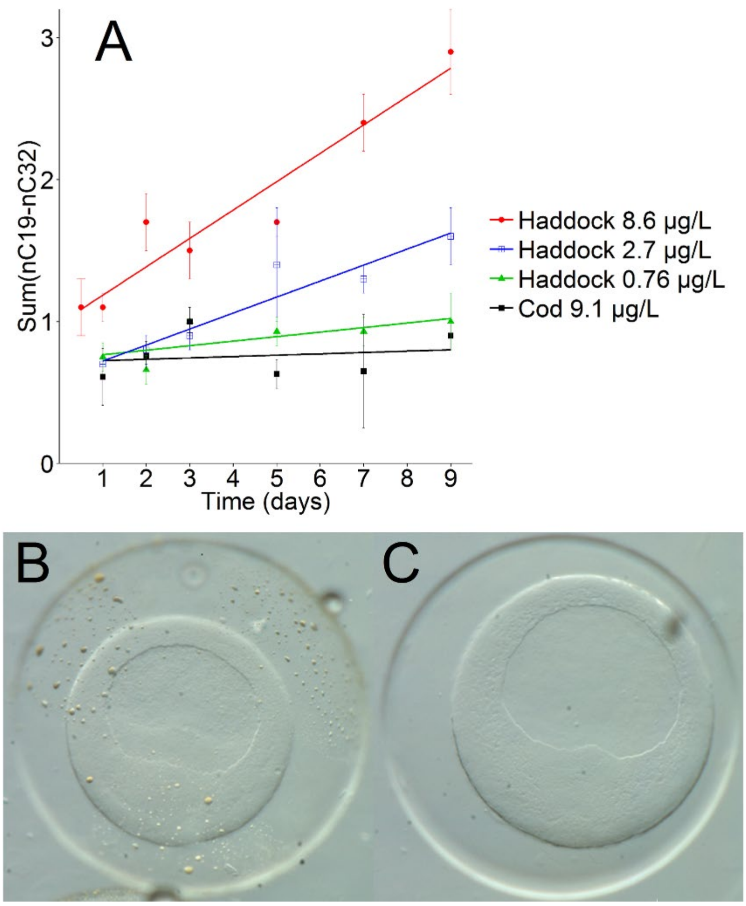

Figure 3.3: Haddock (B) and cod (C) embryos exposed to 600 µg/L crude oil dispersions for 12 hours, where fouling of oil droplets on the chorion of the haddock egg can be observed. In panel A, the relative response of alkanes (Σ(nC19-nC32)) normalized to the response of internal standard pyrene-d12, during the uptake period for three doses of crude oil exposed haddock and the highest exposure dose for cod. Error bars represent one standard deviation (n = 3). A linear trendline is fitted to each group (R2 = 0.926, 0.921, 0.530 and 0.023 for haddock 8.6, 2.7, 0.76 and cod 9.1, respectively). Source: Sørensen et al. 2017.

It is unknown whether PAH cardiac toxicity can be induced in fish larvae drifting through an offshore production field during active discharge of PW.

Summary and Conclusions

The study concludes that research has yet to find reasons for claiming that Barents Sea ecosystems and organisms are systematically more sensitive to PW associated contamination than comparable ecosystems and organisms at other *offshore fields. Certain species within both categories (Arctic and non-Arctic) appear to be more sensitive than others, and research to unravel the reasons for the differences in species sensitivities is ongoing.*

Based on the relevant scientific literature the expert group also concludes that the possible ecological risk associated with offshore PW discharges is most probably not larger at offshore fields of the Barents Sea than elsewhere on the NCS, and by all practical means this risk is negligible compared to the much bigger threat to these systems from global warming. However, they emphasize that there are still many unknowns in this field of study, as only a relatively small number of PW effect studies provide high-quality data for sensitivity comparisons of Barents Sea and non-Barents Sea organisms/systems.

Both laboratory experiments and field surveys suggest that detectable exposure as well as some quite modest impact responses can be induced in fish and mussels when these are confirmable exposed to PW, e.g. when they are kept within the PW plume in the water column relatively close (some hundred meters to a few km) downstream of the PW discharge point. Similar impacts have yet not been demonstrated in wild fish when they are collected in PW influenced areas.

Similarly, impacts were modest in laboratory exposed organisms when these where exposed to PW associated contaminations at high field-realistic concentrations. The typical modest responses found suggest that the overall risk for PW discharges to induce adverse impact in populations of wild fish and possibly other pelagic organisms is low. A low-risk situation is also widely supported from studies using environmental risk modelling procedures for environmental impact and risk assessment of PW discharges offshore.

1.8 Toxicity of PW or constituents

There are still knowledge gaps on the possible impacts on the marine environment from release of oil and chemicals from the offshore industry. Many gaps are with time bridged by knowledge obtained in different research projects, and the gaps are narrowed in the following section where the most relevant of recent scientific articles and other materials are presented. Existing monitoring data does not allow making final conclusions on whether the observed biological responses are of significance for marine life and ecosystems.

Based on chemical analysis of PW from 25 different Norwegian platforms and toxicological data (LC50/EC50), de Vries & Jak (2018) estimated the relative contribution from individual substance groups to the overall hazards. For most platforms the substance-based hazard was dominated by the combined group of production chemicals, the aliphatic hydrocarbons and the organic acids. Averaged over all 25 platforms; production chemicals contributed with 41% to the total hazard, aliphatic HC with 26%, organic acids with 24%, BTEX with 5%, phenols with 1.5%, PAHs with 1.2%, naphthalenes with 0.5% and, metals with 0.3% (calculations based on Table 5.1 in de Vries & Jak (2018)).

1.8.1 Fish

The use of caged fish to monitor the accumulation (and metabolisation) of PAH discharged with PW need to be discussed. Realistically, the exposure of pelagic fish (schooling or solitary) to PW cannot be inferred from caged fish data (e.g. on PAH *metabolites* and various biomarkers). In addition, a recent behavioural study has shown that fish (European Seabass) are able to avoid water with elevated PAH concentration (Claireaux et al., 2018). This means that populations of “reef” fish, attracted to fixed objects (e.g. platform substructures), would be less exposed to PW than their close proximity to the PW discharge point would suggest, simply because they avoid the PW plume. However, the prey may not be able to avoid the plume thus leading to a possible exposure via food intake.

Recent studies (Lindberg et al. 2017, Jayasundara et al. 2017) show that the fish genus *Fundulus* living in an extremely PAH contaminated site (US superfund site) is able to adapt to high exposure rates by metabolizing PAH and maintain a “healthy population” at the cost of higher level of basal oxygen consumption, which resulted in lower maximal metabolic rates and aerobic scopes (measured in swimming respirometer) than *Fundulus* from a reference population. In contrast to fish from the reference site, fish from the polluted site showed adaptation to PAH, insignificant cytochrome P450 activity and low incidences of developmental cardiovascular deformities when exposed to dissolved PAHs (either single PAHs or complex PAH mixtures). Unfortunately, the metabolic costs of the observed biomarker responses (production) in fish around platforms (caged or free living) have not been quantified. Hence, evidence of potential impacts at organism or population level is not available.

Surely, there would be energetic costs related to eliminating PAH from tissues and break-down and eliminating PAH-metabolites from the bile. Estimating such costs would allow to quantify the reduction in fitness and could be quantified numerically rather than calculating risks for species eliminations (Beyers et al. 1999). Without such assessments of energetic costs of adapting to toxicant exposures, the predictions of population impacts based on biomarker values will highly speculative.

Study of bioenergetics in embryo killifish throughout development showed that the basal oxygen consumption rates were much elevated in embryos from the polluted site relative to embryos from the control site. Furthermore, juvenile F1 fish from the polluted site had significantly lower maximal metabolic rates and aerobic scopes than juveniles from the control site. Such results indicate that populations of killifish that have adapted or evolved to withstand the toxicity associated with PAHs consequently have altered energetic (increased) metabolism to cope with PAH metabolism. A reduced maximal scope (for metabolism or swimming speed) may make the PAH-resistant killifish more vulnerable to other environmental and anthropogenic stressors.

Ecotoxic studies on produced water indicates that haddock is more sensitive to PW than cod, e.g. a study by Hansen et al. (2019), found reduced haddock embryo size and increased hart beat after four days of exposure to 3.9 µg/L naphthalenes + 6 µg/L PAH (extracted from PW). The extract was roughly equivalent to 2% of the undiluted PW.

Nepstad et al. (2021) developed a toxicokinetic-individual-based model coupled to an existing transport and fate model (DREAM), and used it to study uptake of polycyclic aromatic hydrocarbons from produced water in early life stages of Atlantic cod. The highest levels of total internal PAH concentration was 1.2 nmol/g (198 ng/g), with 95-percentiles generally below 0.15 nmol/g (27 ng/g), which are below thresholds that are expected to cause chronic effects.

From Bakke et al. “Environmental impacts of produced water and drilling waste discharges from the Norwegian offshore petroleum industry” Marine Environmental Research 92 (2013) 154-169:

The greatest concern is linked to effects of produced water. Alkylphenols (AP) and polyaromatic hydrocarbons (PAH) from produced water accumulate in cod and blue mussel caged near outlets, but are rapidly metabolized in cod. APs, naphthenic acids, and PAHs may disturb reproductive functions, and affect several chemical, biochemical and genetic biomarkers. Toxic concentrations seem restricted to <2 km distance.

A recent meta-analysis building on 221 studies (Santana et al. 2018) concluded that among 9 biomarkers only two (EROD and GST) were robust biomarkers to assess PAHs effects in fish. Despite significant responses of EROD and GST levels to increased PAH concentrations, robust translation into impacts at organism and population level is not possible.

However, if accepting a biomarker concept, fish (and probably also mussels) already adapted to elevated PAH concentrations probably would not show significant responses in biomarker activity when exposed to additional PAH concentrations. Hence, in case of adaptation of species/populations to pollution levels, low biomarker response may result in a false negative, i.e. lack of biomarker response may be interpreted as if the pollution level in the environment is low with insignificant impacts on resident populations.

1.8.2 Mussels

Norway has a national guidance (M-408, revised in 2020) for environmental surveillance of petroleum-related activities at sea, including water column monitoring. The guideline presently focuses on *Mytilus edulis* and fish. Including algal communities in monitoring studies could be considered as well as other species, analytical methods and biomarkers in order to target future WCM.

The increasing seawater temperatures allows for southern species to spread further north. The Norwegian guidelines for environmental monitoring of petroleum activities on the Norwegian continental shelf recommends only *Mytilus edulis* and Pampanin et al. (2019) has highlighted this as a point to consider. Although bioavailability of PAHs and heavy metals may differ between species, a comparative study showed that the three related species *Mytilus edulis*, *M. galloprovincialis* and *M. trossulus* show similar accumulation rates of heavy metals (Cd, Zn) (Blackmore & Wang 2003).

Pampanin et al (2019) observed that caged mussels are able to compensate for stress from PW pollutants. Based on the data from Pampanin et al (2019), both "condition" (dry weight meat relative to (shell length)^3) and lysosomal membrane stability (LMS) in mussels seem unrelated to concentration of total PAH in mussels, which confirms the conclusions of Pampanin et al. However, the in-air survival time (LT50) decreased linearly with increased PAH level, indicating that the exposure has an effect that is not directly correlated with LMS. The mechanism for "compensation" is unclear but could be due to an increase in phytoplankton growth caused by fertilization (with ammonia in PW) or a toxicity-related reduction in planktonic grazing pressure, both leading to increased food availability to mussels. It is important to be able to translate the biomarker-indicated exposure of individuals into an effect to the organism before conclusions on a population scale can be drawn.

It should be possible to quantify impairment of growth/condition in caged mussels deployed around platforms rather than subtle biochemical, histopathological responses. Reduced growth rate compared to a control would have been a much stronger signal for estimating population impact than any biomarker. Despite the present research focus on biomarkers, causal linkages between biomarker responses and impacts at individual and population level have not been demonstrated. Although biomarker responses may mimic the typical sigmoid species sensitivity distribution, it is not a proof of causality between biomarker response and species toxicity.

1.8.3 Copepods

While impact studies on copepods exposed to diluted crude oil or single PAHs are plentiful in the scientific literature (Agersted et al. 2018, Hjorth & Nielsen 2011, Jensen & Carroll 2010, Nørregaard et al. 2014, Olsen et al. 2013), Toxværd et al. (2018) published impact predictions of PW on copepods are few. The studies include Jensen et al. (2016) who exposed adult and nauplii of *Calanus finmarchicus* to artificial PW (containing major classes of polycyclic aromatic hydrocarbons (PAH) and alkylphenols (AP)) at concentrations typically found in PW from offshore oil and gas installations in the North Sea. The nominal exposure concentrations of PW were estimated as half of the median discharge concentration in PW from a Norwegian oil installation immediately prior to discharge. Given the high exposure concentration the observed nauplii mortality was high (as expected), while ingestion and defecation in adult females were much reduced compared to controls. Quantitative information on adult survival was not given.

An alternative model-based approach was applied by Borch et al. (2013) to predict mortality and population impacts of PW discharge *Calanus finmarchicus*. The predicted impacts were low due to high abundance and high reproduction capacity, but a model set-up with large grid cells (800 x 800 m) around platforms would also have indicated low impacts.

In a recent study Hansen et al. (2017) found low mortality in *Calanus finmarchicus* exposed to reconstituted PW (C9-C40 THC) in a dilution series. They were able to estimate a LT50 (144 h) of 4.1 mg THC/L. There is an ongoing study relating to Pampanin et al. (2019), with the aim to quantify total PAH in *Calanus finmarchicus*, stress gene expression and metabolic profiles after a 'realistic PW exposure scenario´ mimicking the dilution of a PW plume.

1.8.4 Use of RBA in WCM

Comprehensive data from laboratory studies on the inherent hazards of the different chemicals and compounds in produced water is available. Results of exposure calculations (RBA) show that certain chemicals could be major contributors to the risk to the marine environment from discharges of PW. There is, however, still a lack of data on chronic toxicity of the different chemicals and a lack of monitoring methods for the relevant chemicals in the marine environment.

Ongoing RBA calculations could potentially generate data that could be used to target further research and monitoring for a better understanding of possible effects. An example of the results of RBA is shown in Figure 3.4. It covers the area around Statfjord A and B and in the Tampen area mentioned above. It indicates that the results of RBA could be used to identify relevant monitoring stations around the offshore oil & gas installations for e.g. water column monitoring activities, if modelling results of the discharge plumes is not available.

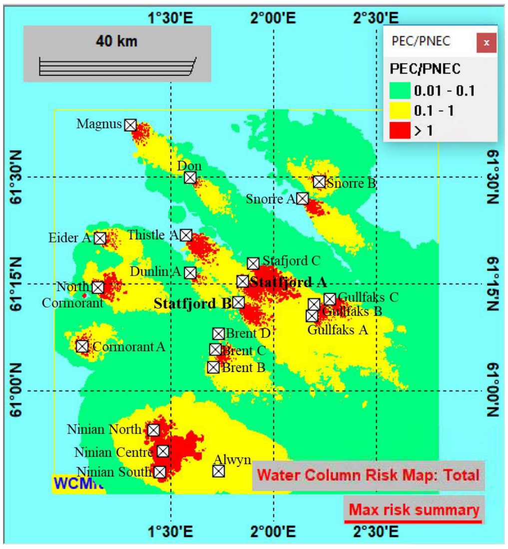

Figure 3.4: Example of the total risk of the area around Statfjord A and B and in the Tampen area in general reported as PEC/PNEC, calculated by DREAM in April 2017. Source: Pampanin et al. (2019)

Recognizing the OSPAR RBA guidelines which allow both Whole Effluent Toxicity (WET) testing and a Substance Based (SB) approach, de Vries & Jak (2018) compared the two methods based on 25 PW effluents sampled at 25 Norwegian platforms. The study focused on comparing hazards rather than risks of the two approaches to minimize dissimilarities between the methods, e.g. by using similar toxicity data on similar test species and not account for fate processes such as biodegradation. Despite numerous uncertainties (e.g. lack of reliable toxicity data for the use in the SB approach), de Vries & Jak found that the acute hazard matched reasonably well in the study when comparing the WET-based approach and the SB approach. On average, the WET-based approach resulted in a slightly higher hazard than the SB approach. When production chemicals were excluded from the SB approach, the difference between the SB and WET based approach was increased, indicating that the SB approach underestimated the hazard more strongly when production chemicals were not included. Limitations and advantages of the two approaches are also described in "Risk Based Assessment of Offshore Produced Water Discharges" by IOGP (2020).

1.8.5 Further studies on use of biomarkers in WCM

Rasmussen and Pedersen (2015) have the following recommendations:

Based on the studies presented above and information on the toxic effects of produced water and effects of other wastes associated with offshore activities, it is recommended to follow an approach similar to the suggestions in Norwegian monitoring guideline (Ref. /29/), where effects on living organisms; caught fish and caged mussels are studied. It is also recommended to supplement these surveys with one or more additional biomarkers for estrogen-specific biological effects (bile estrogenic activity; plasma vitellogenin induction; gonadal intersex) in fish. By monitoring the level of the egg yolk precursor protein Vitellogenin (VtG), the effects of endocrine disrupting substances, such as AP can also be followed. Chemical analysis of samples from mussels and fish should be carried out as well.

Furthermore, it is suggested to consider the inclusion of algal communities in monitoring studies. WET test of PW in the laboratory have revealed that algae are the most sensitive trophic level compared to invertebrates and bacteria. It is therefore of interest to gain knowledge on possible effects of PW on offshore algal communities. One possibility is to take water samples and examine algal community structures and compare these results to algae community structures retrieved from non-contaminated reference stations.

It has previously not been possible to evaluate predicted risk quantitatively with data from monitoring since the predicted risk is based on toxicity test data with model organisms while monitoring is performed using other parameters – as in Norway with biological end-points (biomarkers) measured in ecologically relevant organisms. Hence the biomarker results in previous WCM surveys have not been analysed directly in relation to the predicted environmental risk.

Pampanin et al. (2019) recommend amongst others the following:

The presence of contaminants with genotoxic and neurotoxic effects should be addressed in future surveys, supporting the existing biomarkers (DNA adducts, micronuclei, AchE) with additional ones and also specific laboratory studies.

Due to the possibility of the reproductive status of organisms influencing biological effects responses, the opportunity of commencing the WCM survey outside the mussels and fish spawning season is recommended.

The species selection is a very important factor of the entire study and the use of both benthic and demersal species is highly recommended. The use of multiple species is clearly a key element of the evaluation at ecosystem level. More data on PAH levels in benthic invertebrates and from sedimentation traps would be interesting to better model and understand contribution from ongoing discharges of produced water versus old discharges of oil-based mud in cutting piles.

Method development that better identify and quantify bile metabolites and which PAHs that contribute most to DNA adducts would be beneficial, as well as better understanding of effects through gene transcription studies.

The biomarker data were also integrated using the Species Sensitivity Distributions based on biomarkers. The overall data evaluation based on this approach has been valuable and it is suggested to develop the tool even further to be applied in future WCM surveys.

The method mentioned in the paragraph above is called the "Biomarker Bridges Approach". Through R&D projects funded by the Research Council of Norway in the PROOFNY program the methodology has been developed to enable integration of biomarkers measured during assessment of NCS produced water, with risk related procedures (DREAM-EIF approach; Reed & Rye 2011). It was described in 2017 in two articles in Marine Environment Research (MER): "*Biomarker quantification in fish exposed to crude oil as input to Species Sensitivity Distributions*" (MER 2016.12.002) and "*Species Sensitivity Distributions based on Biomarkers and Whole Organism Responses for integrated impact and risk assessment criteria*" (MER 2016.12.003) both by Sanni et al. The methodology has been tested in the 2017 WCM and is considered a promising tool to decrease the gap between predicted risk and monitoring data. It should be noted however, that similarities between a species biomarker distribution and a species toxicity distribution does not allow to conclude that there is a causal relationship between a biomarker response and a toxic effect.

Conclusions

The continuous discharges of PW are still an environmental concern, as they represent the largest source of crude oil contamination to sea from offshore oil and gas operations. In addition to the natural pollutants in the oil, potentially hazardous production chemicals are also discharged.

The constituents of the PW receiving most attention are phenols, alkyl phenols (AP), naphthenic acid, polycyclic aromatic hydrocarbons (PAH) including naphthalene, phenanthrene and dibenzothiophene (NPD), total hydrocarbons (THC), and metals. The group of AP includes individual substances which have endocrine disrupting effects. Also the group of naphthenic acids includes substances which are expected to have endocrine disrupting effects.

Results of exposure calculations (RBA) show that certain chemicals are major contributors to the risk to the marine environment from discharges of PW. There is, however, still a lack of data on chronic toxicity of the different chemicals and a lack of monitoring methods, which could otherwise both provide a better knowledge on the actual impact in the marine environment from these chemicals.

Data from Norwegian WCM found significantly higher concentrations of PAH and NPD (naphthalene, phenanthrene and dibenzothiophene) in caged mussels located 500 m from an offshore installation compared to reference areas and histopathological analyses of mussels' digestive gland indicated a minor stress condition in caged mussels located 500 m and 1000 m from the platform. Thus, the worst-case exposure (500 m from discharge point) mainly confirmed the exposure by observation of minor stress condition in the mussels. Increased levels of PAHs, alkyl phenols and measured biological responses also suggest exposure of wild fish. The combined exposure to the constituents in produced water may lead to a toxic effect on organisms in the sea. This is reflected in the OSPAR RBA guideline, which allows for the risk to be estimated by either the whole effluent toxicity or by the (summed) toxicity of each substance.

Controlled laboratory experiments have shown that salmon and herring fish fry exposed to low PAH levels (ng to µg per L), induced cardiac defects impacted the fish fry in several critical ways, including reduced swimming performance, prey capture, and prey avoidance, with repercussions on survival and a possible impact on population level. Haddock has been observed to be more sensitive than cod when egg/embryo surface (chorion) was exposed to oil droplets for 12 hours, probably due to the sticky chorion of haddock eggs.

Generally, however, results obtained with field-realistic concentrations indicate that impacts are expected to be modest. The overall risk of PW discharges inducing adverse impact on populations of wild fish and other pelagic organisms is therefore expected to be low.

It is generally accepted that PW effects are limited to the areas where the PW is diluted less than 1000 times, roughly corresponding to distances less than 1000 m from the discharge point depending on the discharge rate, water depth, local currents and other environmental factors. Based on laboratory results where the test organisms are exposed to constant concentrations over several days as well as studies with caged animals placed in the PW plume, acute effects can be expected at such concentrations.

The monitoring of toxic effects in the water column has a focus on biomarkers in fish (especially cod and haddock) and blue mussels (*Mytilus edulis*) and aim to identify sensitive endpoints that can be linked to the exposure to PW. The Research Council of Norway concluded in 2012 that toxic effects such as cell death, genetic change, DNA damage, a change in fatty acid composition and interference with reproduction is detected at concentrations of produced water at 0.1-1% or higher, i.e. when the PW has been diluted less than 100-1000 times. Moreover, the focus of testing of effects of PW has recently shifted towards possible effects of chronic, low-concentration exposures to sensitive endpoints and life stages of marine species such as early life and sexual maturation.

However, the relevance of the constant exposure scenario is questioned because an organism is unlikely to be exposed for days to static concentrations. Drifting plankton (including fish eggs) passing the discharge point may be exposed to high PW concentrations, but because of dispersion and dilution the exposure duration is short. Unfortunately, studies with realistic PW exposure to plankton are not available. For adult fishes, effect or accumulation of PW constituents have not been demonstrated in wild animals caught in PW influenced areas, perhaps because they can avoid polluted areas. This does not mean that laboratory results should be disregarded, especially when the exposure concentrations correspond to dilutions of 1000 times or more. Effects at these low concentrations are observed, however, after weeks of continuous exposure, which are unlikely under environmental conditions. Also sessile organisms are expected to rarely experience constantly high pollution levels, as the direction of a pollution plume change depending on tide, currents, and wind.

Despite the large volumes of PW released, the effects of the constituents appear to be low and mainly seen at biomarker level. However, the causality between the biomarkers and toxic effects and impact at organism and population levels remains to be proven. Other anthropogenic factors are difficult to exclude when assessing the impact of PW in marine ecosystems. Whilst, the conclusions from OSPAR Quality Status Report 2010 are still valid: "*While some biomarker responses to contaminants in produced water can be observed, indicating exposure to produced water, no causal relationship has been identified that can links these observations to impacts to the organism, populations or the ecosystems as such*", further investigations are needed to establish, whether such relationships exists.

RBA has been developed during the last decade as a tool for benchmarking the environmental risk of the PW and as a means to identify and phase out the most toxic chemicals. RBA is based on modelled PEC values and PNEC values translated into an Environmental Impact Factor (EIF) or an impact distance. The PNEC values are based either on testing the toxicity of the whole effluent (WET) or a substance-based (SB) approach. The main purpose of RBA is as a risk management tool to identify risk reduction measures and benchmark site specific risk reductions. RBA cannot be used to assess the impact of PW.

To gain further experience and obtain knowledge on possible effects of discharges from the offshore oil & gas sector in wider parts of the OSPAR marine area it is recommended that new and additional WCM activities are initiated in the coming years. This may include assessment of effects on algal and zooplankton communities. Ecosystem models may also add to the knowledge of impacts of PW at ecosystem level.

Another approach would be to apply the WET approach along with modelling of PW dilution. Briefly, a mesocosm set-up with natural water column species exposed to PW at different dilutions will enable calculation of EC50/LC50 values for a range of species. This can be used as input to modelling of the mortality among different plankton species present in the water column passing a platform area. The mortality of (zoo)plankton groups in the PW plume can hereafter be quantified for each model time step applying a Reduced Life Expectancy (RLE) model which relates exposure time and exposure concentration with lethal toxic effects. Connell et al. (2016). The Impact at ecosystem level can then be quantified by comparing the accumulated number of dead plankton passing through the area with active PW discharge with a baseline (without discharge of PW) as applied by Borch et al. (2013).

Concerns whether Arctic species are more vulnerable towards pollution remains to be proven. The currently available research shows that sensitive as well as more tolerant species are present in both temperate and arctic areas, and that the ecologically rich arctic areas like the temperate can adapt to the relatively low pressures from the release of PW.

Exposure to PW at concentrations corresponding to the levels in the plume at close distances from the discharge point, e.g. < 1000 meters, can be detected in fish and mussels in laboratory experiments and in field studies indicating modest impacts. The typically modest responses to PW discharges observed in laboratory studies imply that the overall risk of negative impact on populations of fish and possibly other pelagic organisms is low. An overall low-risk situation is also supported by modelling of the environmental impact and risk assessment of offshore PW discharges.

1.9 Gaps and recommendations

Based on the review of the available literature and to conclusions drawn above a number of recommendations for further work is suggested:

- Development of methods for monitoring the impact of offshore chemicals present in PW, focusing on the chemicals that RBA has shown are major contributors to the risk to the marine environment from discharges of PW.
- Additional species could be included in the evaluation of possible impacts on communities in the water column. To obtain more knowledge on impact at community level a mesocosm set-up with natural water column species could be applied to derive EC50/LC50 and Reduced Life Expectancy (RLE) at relevant exposure durations for a range of species.
- It would be possible based on such data to quantify the impact by modelling of the mortality among different plankton species present in the water column passing a platform area.
- Effects at biomarker level are observed in water column species at low concentrations of PW. However, a causal relationship between these observations and an impact at population or ecosystem level remains to be identified.

Seabed Monitoring Programs (SMP)

It is generally expected that PW is diluted in the water phase, however, hydrophobic chemicals in it may adsorb to the sediment, especially in shallow water or a downward trajectory of the PW plume. Due to concerns of pollution from cuttings and drilling fluids, there are long-term monitoring records available for bottom surveys and they have been included into the report to provide the full picture of environmental monitoring in the OSPAR area as well as possible inspiration for future water column monitoring programs. Lastly, in case of heavy pollution of the sediments, they may act as a source of pollution for the water column.

From Bakke et al. (2013): *At the peak of discharge of oil-contaminated cuttings fauna disturbance was found at more than 5 km from some platforms, but is now seldom detected beyond 500 m. Water-based cuttings may seriously affect biomarkers in filter feeding bivalves, and cause elevated sediment oxygen consumption and mortality in benthic fauna. Effects levels occur within 0.5-1 km distance. The stress is mainly physical. The risk of widespread, long term impact from the operational discharges on populations and the ecosystem is presently considered low, but this cannot be verified from the published literature*.

1.10 Denmark 1989 - 2015

In 2017 Oil Gas Denmark produced the report “Descriptor-based review of 25 years of seabed monitoring data collected around Danish offshore oil and gas platforms”.

A method based on Marine Strategy Framework Directive descriptors was for the first time used around Danish oil and gas platforms to assess the environmental status (EnS); a score that integrates biological and chemical sediment data. Quantitative deviation from reference areas is indicative of some degree of impact on the benthic ecosystem (though not necessarily significant). The following text is extracted from the report.

Monitoring program and method

The Danish seabed-monitoring program has been conducted every third to fourth year since 1989, with a design set to detect “point source” impact of discharges. Sampling design follow the general standard cross-design centered around the platform similar to that conducted around other oil and gas monitoring across the North East Atlantic regions (OSPAR 2004, 2007). Samples are taken at about 20 stations located at increasing distance from the platform centre (100, 250, 750, 1500, 3000, 5000 m) in four directions (N, S and E, W) and at least one station located more than 10 km away from any other platforms is selected as a platform reference station. The interval for monitoring around the same platform ranged from few months to up to about 10 years depending on the nature and frequency of the drilling activities. Monitoring frequency was decided in agreement with the Danish Authorities.

Most of the Danish processing and producing platforms (Dan F, Gorm, Halfdan A, Harald, Tyra E, Siri and South Arne) and three satellites platforms have been monitored (Kraka, South Arne North Wellhead platform (NWP), Valdemar B). The latest monitoring events were at Dan F in 2015, Gorm (2015), Halfdan A (2012), Harald (2015), Kraka (2002), NWP (2015), Siri (2015), South Arne (2012), Tyra E (2009), Valdemar B (2009). Additionally, 15 distinct reference stations in the North and 15 platform reference stations in the South were sampled with several references stations repeatedly sampled over time representing a total of 32 reference conditions in the North and 44 in the South.

A comprehensive dataset of more than 700 benthic fauna samples and 300 sediment samples collected around O&G platforms 1989 and 2015 was used for determination of regional reference conditions and a quantitative assessment of environmental status focused on four MSFD descriptors: Biological diversity (D1), Non-indigenous species (D2), Sea-floor integrity (D6) and Contaminants (D8). The four descriptors were scored using a linear scale ranging from 100 (i.e. at least as good as reference conditions) to 0. Descriptors score were integrated into a single EnS score for each station located between 100 and 5000 meters from platform. The assessment of environmental status (EnS) score is illustrated in Figure 5.1.

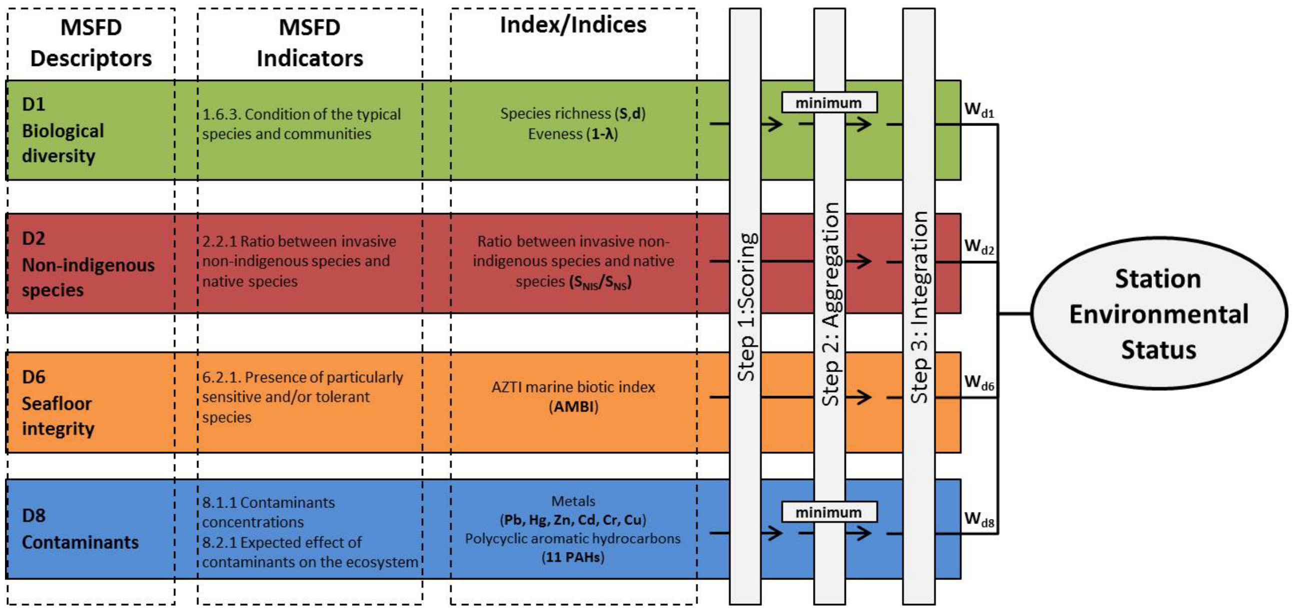

Figure 5.1: Overview of stepwise approach for assessment of station environmental status (OGD 2017).

Results

Heavy metals and polycyclic aromatics hydrocarbons (PAHs) sediment background reference levels (BRL) defined at Northern and Southern reference stations were generally in the low-to-mid range of North Sea sandy sediment concentration (Stevenson et al. 1995, Bjørgesæter & Gray 2008, OSPAR 2013). Generally, metals and PAHs sediment concentrations were relatively lower at southern stations compared to northern stations – an observation typical[8] for relatively shallower and sandier sediment (Bach & Robson 2008, Bjørgesæter & Gray 2008). Metals and PAHs are trace contaminants present in drilling mud, drill cuttings and produced water discharges and it is therefore expected that elevated concentrations would be found in surface sediment stations close to platforms (Neff 2005, Neff et al. 2011).

Contaminants accumulation in sediment is dependent on discharge characteristics (e.g. discharge rate depth and contaminant concentrations), local environmental data (e.g. currents and temperature) and contaminant specific properties (e.g. sedimentation or degradation rates; Neff et al. 2011). Contaminants concentrations within 750 meters of platforms were usually two to three times that of background conditions and below OSPAR ERLs suggesting that the impact of individuals contaminants on the benthic fauna was unlikely (Bjørgesæter & Gray 2008, OSPAR 2013). Concentrations measured around Danish platforms were usually one or two orders of magnitude lower than that found close to cutting piles in the North Sea (Breuer et al. 2004). In shallow Danish waters, tide and currents are sufficient to prevent formation of drill cuttings piles and cuttings are dispersed (Breuer et al. 2004).

Pyrogenic PAHs were the dominant form of PAH at the sediment surface at 70% of stations – a result similar to that found by Boitsov et al. (2013) on the Norwegian continental shelf. Industrial emissions and fossil fuel combustion for land transportation and for domestic use are the primary source of PAH emission to the atmosphere and our results are therefore likely reflecting the intensive maritime traffic, industrial activity and large coastal population of the region (EC 2008, Boitsov et al. 2013). The proportion of petrogenic PAH increased closer to the platform and petrogenic PAH were clearly present at the closest 100-meter stations suggesting that oil contamination has occurred.

The majority of stations scored relatively high and above 90. Descriptors scores were significantly lower up to 1500 meters (D1) and 250 meters (D6 and D8) from the platform. There was no indication that NIS presence and abundance is related to the presence of O&G platform. Lower EnS scores were observed up to 1500 meters from the platform 5 years

[8] Comment: Sediment concentrations of heavy metals and PAHs were lower at southern stations compared to northern deeper stations due to lower sediment content of organic matter and clay and because large waves would have sufficiently energy to affect bed shear stress and induce resuspension at the southern stations (Stanev et al. 2008)

after drilling operations. There were regional differences with lower scored observed around deeper northern platforms. Based on high EnS scores and resistance and resilience of the benthic ecosystem to O&G operational discharges, it is concluded that Environmental Status around O&G platforms in the Danish North Sea is Good. Our conclusions are consistent with that drawn from previous benthic fauna analysis in Denmark or results from other monitoring programme in other O&G areas of the North Sea.

The environmental status of the bottom sediment could be linked to the pollution plume coming from a PW discharge point, especially for shallow water areas. Please refer to section 5.2 for further discussion of the connection.

1.11 Denmark 2018

The following text is extracts from four reports prepared on request from Total and Hess Denmark by DHI (2018a, 2018b, 2018c, 2018d), on offshore chemical and biological monitoring around oil and gas platforms:

- Monitoring around the Gorm platform - 2018
- Monitoring around the Tyra E platform - 2018
- Monitoring around the Dan F platform - 2018
- Monitoring around the South Arne platform - 2018

The assessment used an approach described by Oil Gas Denmark (OGD 2017) and the Marine Strategy Framework Directive (MSFD):

A chemical and biological monitoring of the seabed around four platforms (see Figure 5.2) was performed in May-June 2018. Three of the platforms (Gorm, Tyra E and Dan F) are located in the southern part of the Danish sector of the North Sea, between approximately 188 and 210 km from the Danish west coast. The fourth platform (Syd Arne) is located in the northern part of the Danish sector of the North Sea approximately 243 km from the Danish west coast. The seabed was monitored at 18 platform stations located at a distance of 100 m, 250 m, 750 m, and 1500 m in the north, east, west and south direction around the four platforms and at 3000 m to the east and west. In addition, one or two local reference stations and one regional reference station placed at more than 10 km from each of the four platforms were surveyed.

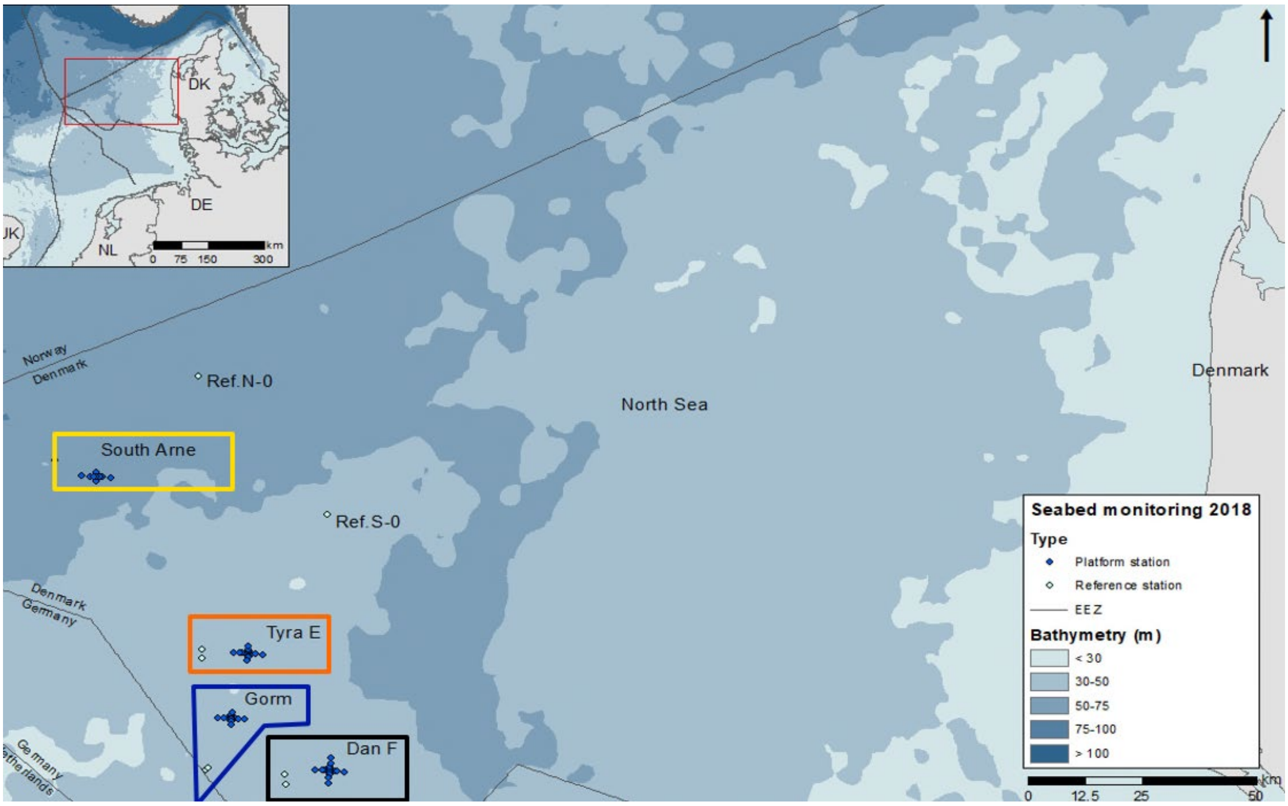

Figure 5.2: Map of the 2018 Seabed Monitoring Area on the DCS

Two Marine Strategy Framework Directive pressure descriptors and two state descriptors were assessed in the SMPs:

- Descriptor 1: Biological diversity (state)
- Descriptor 2: Non-indigenous species (pressure)
- Descriptor 6: Seafloor integrity (state)
- Descriptor 8: Contaminants (pressure)

Up to 17 individual indicators were compared against specific reference levels and used to calculate individual indicator score (or index). Then, the lowest indicator score was used to define the descriptor index. Subsequently, the stations' Environmental Status (EnS) score was estimated by a weighted average of the four descriptors scores (3 for state descriptors and 1 for pressure descriptors). Index was built to range from 0 (bad state/extreme pressure) to 100 (similar to reference levels). Stations were classified based on their EnS scores: High when score was equal to 100, good (75-100), moderate (50-75), poor (25-50), bad (0-25).

Results

Based on the 2018 seabed monitoring, the calculated Environmental Status (averaged over descriptors and over four directions (N, E, S, W from platforms) ranged between 89 and 100. Around Dan F platform, EnS was significant reduced close to the platform (100 m) primarily due to reduced biodiversity (D1), and to elevated concentration of pollutants (D8). At the South Arne the EnS was reduced 250 m from the platform due to reduced biodiversity (S & E directions), presence of non-indigenous species (D2) and reduced seabed integrity (D6) (N, E and S directions). Around Gorm and Tyra E platforms EnS were rather high, uniform and independent of distance from the platforms (Table 5.1).

The reason for reduced seabed EnS near to Dan F platform is unknown, but potential impact from PW discharge cannot be ruled out, as discharges from Dan F platform is 4-to-12 times larger than discharges from the other three platforms. Briefly, the PW is discharged at a depth of 29 m and, having a higher density than the surrounding seawater PW tends to remain near the seabed allowing PW constituents to interact with seabed through adsorption and precipitation.

Table 5.1: Overview of the Environmental Status of seabed scores at 4 platforms monitored in 2018 separated into distances from the platforms and averaged across distances. Last column shows the accumulated PW discharge in 2017 (in 1000 m^3) (ens.dk).

	100 m	250 m	750 m	1500 m	3000 m	PW discharge
Dan F	89	97	99	96	100	10,726
Gorm	98	98	96	95	99	2,682
Tyra E	100	99	96	98	100	846
South Arne	97	93	100	100	98	2,408

Oil Gas Denmark's presentation "SEABED MONITORING 2018 SUMMARY RESULTS, January 2019" presented at a meeting in the Danish Environmental Protection Agency on February 26, 2019 indicates that the findings from 2018 confirm general results from the 1989-2015 review.

1.12 Norway 2017 – Region IV

Statoil Petroleum, Wintershall, Engie E&P Norge and Norske Shell commissioned Akvaplan-niva AS to carry out the regional environmental survey in Region IV in the North Sea (PO 4503497081). The following text is based on the report "Environmental Survey in Region IV, 2017, Summary Report, Akvaplan-niva AS Rapport: 8622-04.

Monitoring program and method

The fields included are Statfjord A, Statfjord B, Statfjord C, Statfjord Nord, Statfjord Øst, Gullfaks A, Gullfaks B, Gullfaks C, Gullfaks satellites, Visund, Visund Nord, Visund Sør, Vigdis northern templates, Vigdis D, Vigdis F, Tordis, Snorre B, Snorre A TLP, Snorre EP, Kvitebjørn, Valemon, Vega, Nova (earlier Skarfjell), Gjøa and Knarr (earlier Jordbær) (see Figure 5.3). In addition, samples from 16 regional stations were collected.

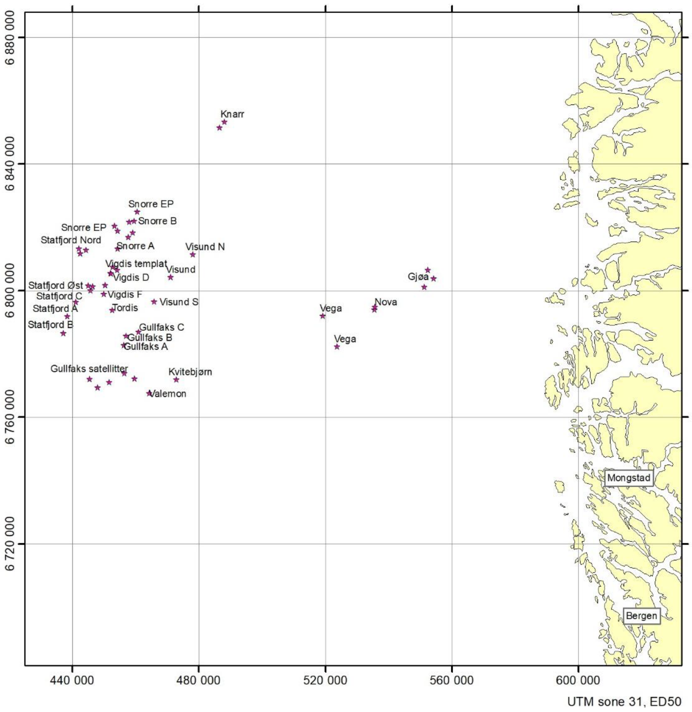

Figure 5.3: Map of Region IV Seabed Monitoring Area 2017

During the field work from 19.05 to 07.06. 2017 samples from a total of 367 stations in the region were collected. Of these, only chemical samples were collected at 146 stations. The field work was carried out without interruption. The samples were collected by use of a 0.15 m2 combi grab or a 0.1 m2 van Veen grab depending on the water depths and *sediment conditions. Station depths in Region IV vary from approximately 123 m in the west (Valemon) to 410 m in the east (Knarr). The sediment composition is mainly fine sand in the shallower part and silt and clay in the deeper part.*

Fauna disturbance was estimated using number of individuals, number of taxa and the diversity index H' (Shannon-Wiener) for each site. The results were compared to the Limit of Significant Contamination (LSC) value, which is a statistically calculated concentration limit for chemical contamination based on reference values from regional or sub-regional stations (Norwegian Environment Agency, 2020).

Results

For the region as a whole, there is a decrease in sediment area contaminated with total hydrocarbons (THC) above 50 mg/kg, from ~7.08 km2 in 2014 to ~5.31 km2 in 2017. The main reason for this reduction is that the sediments at Statfjord A, Statfjord B, Statfjord C, Gullfaks satellites, Vigdis northern template and Vigdis D in 2014 were contaminated with THC, whereas this was not the case in 2017.

The sediments at Snorre B stood out with high maximum concentrations of THC being 14793 mg/kg. It was only at Gullfaks satellites, Gullfaks B, Statfjord Øst, Statfjord Nord, Visund Sør, Visund and Visund Nord where the content of THC in the sediments was below the LSC-value at all stations.

The highest level of barium was found in the sediments at Nova (SKF-19) with a concentration of 39200 mg/kg and at all fields in Region IV, the sediments had at least one or more stations contaminated with barium (2xLSC) in the present survey. For the other metals (As, Cd, Cr, Cu, Hg, Pb and Zn), the sediments at Statfjord A, Statfjord B, Statfjord C and Gullfaks A stood out, with high maximums values, clearly above the respective LSC-values. At Gullfaks satellites, Nova and Vega, the sediments were contaminated with all the other selected metals.

Polychaetes dominated the fauna with 71 and 50 % of the total number of individuals and taxa, respectively. The most abundant polychaete was Siboglinidae indet., which at one station at Snorre B occurred with more than 46000 individuals. Large differences in the number of individuals and taxa were recorded at many of the fields and at the regional stations. Also the diversity varied largely due to the dominance of some polychaetes at some stations. This was partly caused by the occurrence of Siboglinidae indet., but also the polychaetes Capitella capitata and Filograna implexa. The C. capitata occur in high numbers in sediment with a high amount of THC, while the other species is a colonial, tube building polychaete which may occur in high numbers without any connection to contaminated sediments.

The total area in Region IV with disturbed fauna was calculated to be 10.02 km2 compared to 11.28 km2 in 2014. It should be pointed out that no faunal disturbance was registered at nine of the fields monitored in 2017 (Gullfaks A, B and satellites, Visund, Visund Sør, Vigdis templates, Gjøa, Knarr and Vega).

1.13 Norway 2017 – Region I

ConocoPhillips, AkerBP, Lundin, Statoil, Spirit Energy and Repsol commissioned DNV GL and SINTEF MOLAB to carry out a regional environmental survey in Region I in the North Sea (Ekofisk Area) – see Figure 5.4. The following text is based on the report "Offshore Monitoring Region 1, Summary Report, 2018-0125, Rev. 01, 2018-11-14"

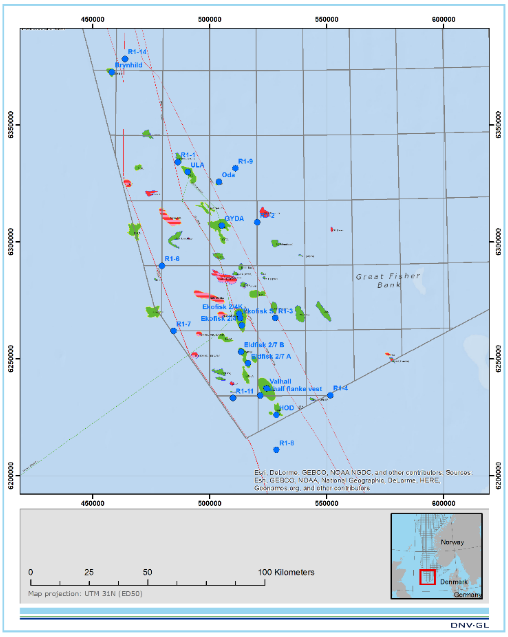

Figure 5.4: Map of Region 1 Seabed Monitoring Area 2017

Monitoring program and method

The survey included collection for chemical and biological analyses of sediments, as well as characterisation of sediments. The fieldwork was conducted according to the Environmental monitoring of offshore petroleum activities (M300 | 2015) and DNV GLs and SINTEF MOLABs accredited methods for this type of work (Test 083 and 032).

On the basis of sediment characteristics and the results from the chemical analyzes of the regional stations the region is divided into two subregions (see Figure 5.5):

- *Northeastern subregion: Ula, Gyda, Oda (previously Butch Main), Brynhild*
- *Southwestern subregion: Ekofisk Kompleks og Ekofisk B&K, Ekofisk 2/4 A, Eldfisk 2/7A, Eldfisk 2/7 B, Valhall, Valhall Vest, Hod*

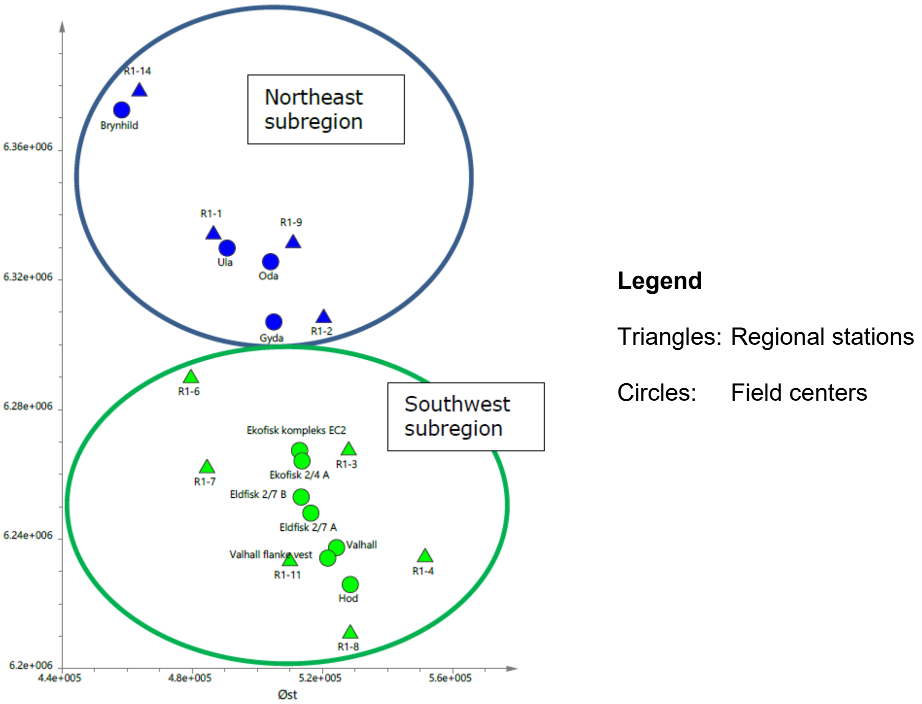

Figure 5.5: Map of sub-regions for Region 1 Seabed Monitoring Area 2017

A limit of significant contamination (LSC) based on the results from the period 1996 – 2017 for each of the two sub-regions was calculated, ref. Table A-5.2. *The values are used to decide whether each of the field specific stations have elevated (contaminated) concentrations or not.*

Table A-5.2: Limit of significant contamination (LSC) based on the results from the period 1996 – 2017 the two sub-regions.

mg/kg	*THC*	*PAH*	*NPD*	*Ba*	*Cd*	*Cr*	*Cu*	*Hg*	*Pb*	*Ti*	*Zn*	*As**
$LSC_{96\text{-}17\ northeast\ Reg1}$	4.3	0.045	0.02	44.4	0.02	8.9	0.81	0.01	8.8	114	10.6	3.4
$LSC_{96\text{-}17\ southwest\ Reg1}$	5.0	0.056	0.02	77.8	0.02	8.0	1.02	0.02	7.7	72	6.7	5.4

**) As calculated from 2017*

Results
The 2017 survey shows:

- *The total organic carbon (TOC) content vary from 0.22 – 0.88 % in the northeast subregion, and 0.23 – 0.60 % in the southwest subregion.*
- *The total hydrocarbon (THC) concentrations vary from 1 -33 mg/kg in the northeast subregion, and 2 – 600 mg/kg in the southwest subregion.*
- *In the northeast subregion it is found THC > LSC 96-17 northeast Reg1 (4 mg/kg) at four stations at Gyda, four stations at Ula and one station at Brynhild. It is not found THC > LSC96-17 northeast Reg1 at Oda*
- *In the southwest subregion it is found THC > LSC96-17 southwest Reg1 (5 mg/kg) at most stations in all fields, except from Valhall Vest where no concentrations above LSC is found.*
- *The concentrations are either unchanged or decreased compared to previous surveys in both subregions. There is an increase of the THC concentration at EKOA13.*
- *In the northeast subregion it is found polyaromatic hydrocarbons (PAH) and NPD > LSC96-17 northeast Reg1 (0.045 mg/kg PAH and 0.02 mg/kg NPD) at five stations at Ula and three stations at Gyda. In the southwest subregion it is found PAH and NPD > LSC96-17 southwest Reg1 (0.056 mg/kg PAH and 0,02 mg/kg NPD) at several stations at Ekofisk Kompleks, Ekofisk A, Eldfisk A and Valhall. The Ba concentrations vary from 9 – 2320 mg/kg in the northeast subregion, and from 45 – 9210 mg/kg in the southwest subregion.*
- *In the northeast subregion it is found concentrations of metals > LSC at BRY13, GYDA18 and serveral stations at ULA. Compared to previous surveys there is an increase in metal concentrations at BRY13.*

- *In the southwest subregion it is found concentrations of metals > LSC at all fields. There is an increase in metal concentration compared to previous surveys at Eldfisk B and Ekofisk A. It is at Ekofisk Kompleks and Ekofisk A where the highest concentrations of metals are found.*
- *The abundance of the polychaetes G. oculata, P. jeffreysii and S. bombyx varies significantly between stations and between years, which has implications for diversity indices. The benthic fauna at the regional stations is considered undisturbed by the petroleum activities in the area.*
- *The soft bottom fauna of Valhall Flanke Vest, Brynhild, Eldfisk A and Oda is considered healthy and undisturbed.*
- *At the other fields, development in the bottom fauna is positive, but some stations are still considered to be disturbed. Nine of the stations considered disturbed in 2014, are regarded as undisturbed in 2017; one at Gyda, four at Eldfisk A and four at Valhall.*

1.14 United Kingdom 2015 - 2016

Two linked regional sediment and fauna surveys was undertaken December 2015 - January 2016 and covering the Fladen Ground and Mid North Sea High areas marked on Figure 5.6 as OESEA3 2015 (Fladen) and OESEA3 2016 (MNSH). The following is extracted from an information sheet provided by the UK Department for Business, Energy and Industrial Strategy.

Monitoring program and method
Sampling points were selected on a stratified random basis, but with no stations closer than 2km from an exploration or appraisal well, or 5 km from a producing installation.

Sediment samples were analysed in line with OSPAR Agreement 2017-02 for sediment grain size, concentrations of trace and heavy metals (Aluminium, Arsenic, Barium, Cadmium, Copper, Chromium, Iron, Lead, Lithium, Manganese, Mercury, Nickel, Rubidium, Strontium, Vanadium, and Zinc), Total Hydrocarbon Content, Naphthalene (128), Phenanthrene/Anthracene (178), Dibenzothiophene (184), Fluoranthene/Pyrene (202), Benz(a)anthracene/Chrysene (228), Total NPD, Total 2 to 6 ring PAH, and Biota using 0.5 mm & 1.0 mm sieve meshes.

The MNSH survey was the first regional survey of the area. Accumulations of biodegradable contaminants were not predicted, given the controls in place for discharges from installations in the area.

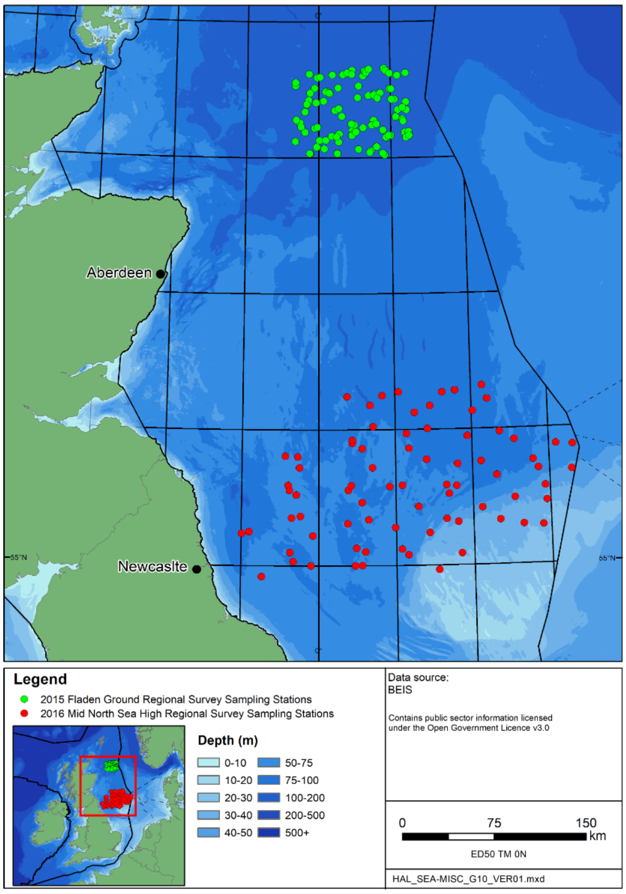

Figure 5.6: Map of UK monitoring Area 2015 - 2016

Results

Seabed faunal results from the Fladen and Mid North Sea High area indicated healthy, diverse seabed communities, apparently unaffected by discharges in the areas and with no elevations of any opportunistic species typically associated with disturbance or contamination effects.

Concentrations of metals and hydrocarbons present were below OSPAR Background Assessment Criteria (BAC) for almost all samples and determinands, the exceptions were all close to the BAC concentrations and showed no spatial pattern or between determinand correlation within a sample.

Three stratified random sampling surveys have been undertaken in the Fladen Ground (2001, 2005, 2015) and the hydrocarbon concentrations in sediments in samples and strata show a progressive improvement over time, with concentrations now at or below the OSPAR BAC.

1.15 Conclusions from the SMPs

The sediments of the seabed may be exposed directly or indirectly (via sedimentation of adsorbed fractions) to PW released in relatively shallow waters. Sediments near offshore oil and gas platforms may contain the hydrophobic components present in PW, although the source can also be drilling mud or drill cuttings. Both Danish and Norwegian studies found that the concentration in sediments of petrogenic PAH increases in the areas close to the platforms. However, at 70% of the stations the dominant form of PAH in the sediment surface was pyrogenic, reflecting the intensive maritime traffic, industrial activity and coastal cities in the region. The sediment samples around the Danish platforms were scored with biological diversity and evenness descriptors. Although low scores were observed at one platform at a distance up to 1500m 5 years after drilling operations the general conclusion is that the environmental status near the Danish platforms is good. A similar conclusion was reached after the investigations in 2018. As such, changes to the seabed fauna and quality are local and short-term and the seabed is resilient to disturbances associated with oil and gas operational discharges.

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