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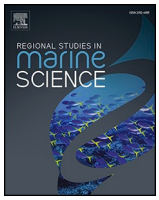

Exposure and effects of synthetic enhanced oil recovery polymers on the Norwegian Continental Shelf

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ABSTRACT

Synthetic polymers are planned to be used for more efficient oil recovery from offshore oil reservoirs. Using synthetic polymers offshore may lead to these being released into the marine environment through produced water (PW) discharges, thereby causing environmental impacts in the ecosystem. In this study, we assess the impacts of discharging synthetic polymers on the Norwegian Continental Shelf (NCS). We use a numerical model called the Dose-related risk and effects assessment model (DREAM) to simulate discharges of polymers into the sea. DREAM assesses impact in terms of environmental impact factor (EIF) values of individual chemicals present in the PW. Two approaches are used: first, using a standard short-time/small-scale/near-field simulation procedure (50 by 50 km); second, using a non-standard long-term/large-scale/far-field simulation procedure (1200 by 1800 km). For the near-field simulations, the impact is assessed by estimating EIF values resulting from the discharge of 200 and 8000 kilodaltons (kDa) molecular weight fractions of Anionic Polyacrylamide (APAM) from a North Sea oil field. The results show higher EIF values for 8000 kDa compared to 200 kDa APAM. Far-field simulations are used because polymers appear to be resistant to microbial degradation and are thus expected to have long residence times in the sea. An increase in concentrations to harmful levels for aquatic species due to repeated discharges from multiple oilfields is thus possible. The results from the far-field simulations are used to establish relationships between the amount of polymer released annually and the resulting highest values of 100- and 75-percentile concentrations. The results indicate that polymers are not expected to build-up on the NCS and there is a significant margin between the expected polymer concentrations and the lowest concentrations at which toxic effects are observed. The established regression equations can be used to indicate maximum expected concentration values for future release scenarios.

1. Introduction

Polymer flooding has been successfully implemented since the 1950s for the purpose of enhanced oil recovery (EOR) from mature oil and gas reservoirs (Standnes and Skjevrak, 2014). The application of polymer flooding increases the viscosity of the injected fluid, thereby displacing/sweeping the oil from the reservoir. A viscous polymer solution is created by dissolving high molecular weight (several million Daltons) polymers at different concentrations (Thomas et al., 2012). Most polymer flooding projects are implemented in onshore reservoirs, with increasing interest in their implementation in offshore reservoirs (Standnes and Skjevrak, 2014; Smalley et al., 2020). Based on the reservoir characteristics, different types of synthetic water-soluble polymers are selected for this purpose (Thomas et al., 2012). The most frequently used synthetic polymers are hydrolyzed polyacrylamides (HPAMs), which are polymers manufactured using acrylamide (AM) and acrylate (AC) monomers. However, the use of anionic polyacrylamides (APAMs), which are polymers manufactured using acrylamido tertiary butyl sulfonate (ATBS) and AM monomer, is being considered, due to emerging challenges related to offshore applications (Hansen et al., 2019; Standnes and Skjevrak, 2014).

Injected polymer undergoes mechanical (due to shear forces acting on the polymer at various stages - including injection through choke valves, well perforations, inflow to production wells), chemical, and thermal degradations in the reservoir (Brakstad et al., 2020; Thomas et al., 2012). The degraded polymers are back-produced along with produced water (PW) during oil and gas production (Zhang et al., 2010). A study from the Shengli oil field in China reported a polymer

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concentration of 170 mg/l in the PW with no details on injected concentrations (Zhang et al., 2010). Although, there is limited data available on the concentration and molecular weight of the back-produced polymer in the PW,it is expected that polymer concentration may be reduced by over 50 %, and the molecular weight is typically five to ten times lower than what is initially injected (Thomas et al., 2012). Although polymers are degraded to low molecular weight compounds, the molecular weight will still be high, and these high molecular weight molecules are resistant to microbial degradation (Brakstad et al., 2020; El-Mamouni et al., 2002; Guezennec et al., 2015). For offshore applications, PW is usually discharged into the marine environment or re-injected into the reservoir. If PW containing polymers is discharged into the sea, aquatic species may be exposed to the polymers, posing an environmental risk to the ecosystem.

So far, data related to the toxic effects of HPAMs/APAMs on marine organisms is limited. The presence of different molecular weight fractions of polymers in the back-produced polymer further complicates the issue, as measuring the toxicity at different molecular weight fractions is challenging. In a study done on assessing the toxic effects of 200-kilo Daltons (kDa) molecular weight fraction of APAM (75 % AM and 25 % ATBS) on early life stages of Atlantic cod, minor effects are observed at 125 mg/l, with major toxic effects seen at a concentration of 6000 mg/l (Hansen et al., 2019). Another study was carried out to assess the toxic effects of three different molecular weight fractions of APAM: 200, 2800, and 8000 kDa on different developmental stages of *Calanus finmarchicus* (Farkas et al., 2020). The lowest lethal concentration where 10 % mortality occurred (LC_{10}) was observed for the first feeding stage of *C. finmarchicus* species exposed to 8000 kDa of APAM (144 mg/L). In this study, we have selected polymers with molecular weights of 8000 kDa and 200 kDa as representatives of the discharged polymers in the produced water for the purpose of assessing their environmental impacts. The choice of the 8000 kDa polymer is relevant for Enhanced Oil Recovery (EOR), assuming a reduction in molecular weight of 20–50 % in the back-produced water. On the other hand, the 200 kDa polymer serves a crucial role in representing the lower end of molecular weight values for degraded polymers found in back-produced water. Moreover, as discussed earlier, the choice of these specific molecular weights was driven by the limited availability of toxicity data for diverse molecular weight polymers.In this study, we assess the environmental impacts of discharging back-produced polymers into the marine environment on the Norwegian Continental Shelf (NCS). We use a numerical model, called the Dose-related risk and effects assessment model (DREAM) (Reed and Hetland, 2002; Reed and Rye, 2011), to simulate the discharge of polymers into the marine environment. The DREAM model is routinely used to assess the environmental impact and indicate risk increases in terms of environmental impact factor (EIF) values of individual chemicals discharged along with PW in the marine environment. The EIF methodology is based on calculating the ratio of predicted environmental concentrations (PEC) to predicted no-effect concentrations (PNEC) of individual chemicals present in the PW (Beyer et al., 2020; Smit et al., 2011). We assess the environmental impacts of synthetic polymers, by using a combination of two approaches. The first approach involves simulations within an area where short-term/small-scale impact is assessed. In the present paper, we call this a near-field area, covering 50 by 50 km from the discharge site. For this, we have used PEC to PNEC ratios of different molecular weight fractions of APAMs to assess environmental impact. The second approach involves longer time simulations, covering a much larger area (1200 by 1800 km from the discharge site), which we have named far-field, in this paper. Here, the possibility of an increase in concentration due to the build-up of polymers repeatedly discharged from multiple oil fields is studied. The second approach is primarily studied because synthetic polymers appear to be resistant to microbial degradation. Resistance to microbial degradation will lead to a much longer polymer residence time within a much larger area than the situation studied in the near-field approach.

2. Materials and methods

2.1. Produced water transport using the DREAM model

Currently, there are several modeling tools available to characterize environmental impacts associated with produced water discharges, including dynamic risk and effects assessment model (DREAM), the pollution risk offshore technical evaluation system (PROTEUS), MIKE, and Delft3D (De Vries and Karman, 2009). For this study, we have chosen the DREAM model to evaluate the environmental impacts of polymers in the marine environment, primarily due to its comprehensive approach that takes into account various key factors influencing fate and effects of chemicals in the marine environment. A Lagrangian particle approach is used in the DREAM model to handle and track all chemicals present in the PW. These particles are advected using a local ocean current's velocity and a random turbulent diffusion component. The model allows the creation of a profile for individual chemicals present in the PW based on their eco-toxicological properties, such as biodegradation, octanol-water coefficient, and toxicity. The mass concentration of chemicals (PEC) dissolved in the PW is calculated within a habitat grid, taking into account vertical and horizontal dilution, as well as mass loss due to biodegradation/evaporation. In this study, mass loss resulting from the biodegradation of polymers is not considered, primarily because these polymers are anticipated to be persistent (Brakstad et al., 2020; El-Mamouni et al., 2002; Guezennec et al., 2015). It's important to note that there is currently lack of data regarding the biodegradation of synthetic EOR polymers in the marine environment.

For each chemical, a species sensitivity distribution (SSD) curve is generated, expressing the potentially affected fraction of species (PAF) as a function of exposure concentrations – which correspond to the PECs in the DREAM simulations. The combined expected impact from all chemicals is calculated based on a multi-substance PAF (msPAF) approach (De Zwart and Posthuma, 2005; Smit et al., 2005). The PNEC (threshold) values are commonly set (by regulatory policy) to the PEC where 5 % or more of the species are expected to be affected (or PEC/PNEC $\geq$1). An EIF volume is defined as a volume of 100,000 m3 (100 m by 100 m by 10 m), and the EIF volumes simulated by DREAM are assigned values of 1 when PEC/PNEC$\geq$ 1. This is done for each time step of the model, yielding sums of EIF volumes and values dynamically that are used to inform about the environmental risk. In addition to EIF values, the DREAM model also calculates the average contribution over time from individual chemicals to these EIF values. In this paper, the contribution to EIF values from different molecular weight fractions of APAMs is estimated. EIF values and contributions to EIF values are routinely used as a decision support tool to assess the environmental impact and indicate risk increases from individual chemicals in the PW. Reed and Hetland (2002) and Reed and Rye (2011) provide a detailed description of the different configurations available, as well as the methodology and equations used in the DREAM model.

Simulation of PW discharge and transport using the DREAM model requires external ocean circulation and wind data. We use an archive of ocean circulation data covering the simulation area over 10 years, i.e., from 2002 to 2011. The data contain the daily average of ocean currents' velocity with a horizontal resolution of 4 km and a varying vertical resolution. Further details related to the generation of ocean currents' data used in the present study are available from Lien et al. (2013). The wind data covering the simulation domain with six hours of temporal resolution are downloaded from Copernicus (Hersbach et al., 2018).

2.2. Near-field simulations to assess the short-term impact

A hypothetical case of implementing polymer flooding using APAM on the Brage oil field on the NCS is assumed. PW discharge containing back-produced APAM and other production chemicals from the Brage field is simulated using near-field simulations. Actual PW discharge data

from the Brage field are used to assess the short-term impact of synthetic polymers. The impact of different molecular weight fractions of APAMs is assessed in terms of EIF values, using the DREAM model. The PW discharge profile contains concentration and eco-toxicological data of all production and naturally occurring chemicals injected and back-produced along with the PW during the oil and gas production process. As mentioned earlier, there are limited data available on the concentration, molecular weight, and toxicity of back-produced polymer in the PW. Hence, three cases with different concentrations of back-produced polymers in PW are assumed for setting up the simulations, i.e., 250, 500, and 750 mg/l.

The aquatic toxicity data of 200 kDa and 8000 kDa APAMs are used to determine the PNEC values (Farkas et al., 2020; Hansen et al., 2019). For 200 kDa APAM, an EC_{10} value (based on developmental effects) from long-term exposure to *C. finmarchicus* is measured at 517 mg/l (range 358–757). In addition, an LC_{10} value measuring the survival of *C. finmarchicus* due to long-term exposure to APAM 200 kDa is measured at 1664 mg/l (range 905–3058). The toxicity data based on short-term exposure of APAM 200 kDa to different life stages of *C. finmarchicus* are also available, all of which report toxicity values higher than 500 mg/l (Farkas et al., 2020). Another study based on long-term exposure of early life stages of Atlantic cod to APAM 200 kDa reported a minor reduction in heart rate at 125 mg/l, with no consistent responses regarding survival and growth observed until concentrations of 6000 mg/l. For 8000 kDa APAM, an LC_{10} value (based on survival) for short-term exposure to *C. finmarchicus* is measured at 144 mg/l (range 118–177). Using all this data as a reference, we assume toxicity values of 125 mg/l and 500 mg/l to be representative of 8000 kDa and 200 kDa, respectively. Furthermore, acute toxicity (LC_{10}) of 2800 kDa APAM exposed to *C. finmarchicus* is measured at 461 mg/l (Farkas et al., 2020). We do not assess the environmental impact of 2800 kDa of APAM separately, but the EIF values of 2800 kDa will be quite close to those of the 200 kDa APAMs because of approximately similar toxicity values.

PNEC values are usually estimated by dividing the lowest available toxicity metric by the relevant assessment factor (AF) (ECHA, 2008). The recommended AF values are typically conservative, as they are meant to be protective of the ecosystem. Depending on the availability of toxicity data for species in different trophic levels, a range of AF values is suggested to determine the PNEC values of chemicals/stressors (ECHA, 2008). Generally, greater availability of toxicity data for different species allows the use of a lower AF, as it reduces the uncertainty. An AF of 50 is recommended when two instances of long-term toxicity data for freshwater or saltwater species representing two trophic levels and one long-term result from an additional taxonomic group are available. Using an AF of 50 can still be valid if data on short-term toxicity studies are available instead of one additional long-term result. As mentioned earlier, for APAM 200 kDa, short-term toxicity data are available in addition to long-term data on species from two trophic levels (Farkas et al., 2020; Hansen et al., 2019). Based on this, we assume an AF of 50 to be valid for APAM 200 kDa. The use of AF can be varied if evidence of toxicity data related to structurally similar compounds is available (ECHA, 2008). The different molecular weight fractions of APAMs are structurally similar. As a result, even though long-term toxicity data for APAM 8000 kDa are not available, an AF of 50 is assumed to be valid. Using the same AF also allows a better comparison of EIF contribution values from APAM 200 and 8000 kDa. Based on this, we define two cases to determine PNEC values for APAM 200 and 8000 kDa, one with an AF of 50 and the other with no AF. Using three discharge concentrations of back-produced polymer and four PNEC values, we run a total of 12 simulations to estimate and compare the EIF values of APAMs. Table 1 summarizes the input parameters used in the near-field simulation to estimate the EIF values of APAMs, and Fig. 1 shows the simulation area.

Table 1
Input parameters used in near-field simulations to assess the short-term impact.

Simulation parameter		Values	
Back-produced concentration of APAM in produced water		250 mg/l	
		500 mg/l	
		750 mg/l	
PNEC	8000 kDa	125 mg/l	No AF
	200 kDa	500 mg/l	
	8000 kDa	2.5 mg/l	AF = 50
	200 kDa	10 mg/l	
Volume of produced water discharged		15,571.5 m^3 /day	
Produced water discharge duration		8 days	
Simulation time		30 days	
Habitat grid		50 * 50 km	
Concentration grid dimensions		100 * 100 * 10 m	
Calculation time step		30 min	
Output time step		6 h	

2.3. Far-field simulations to assess the build-up of polymers

As mentioned earlier, synthetic polymers appear to be resistant to microbial degradation. Hence, the repeated discharge of polymers from multiple oil fields may lead to a build-up of polymers in the sea. We extend our study area from near-field (50 ×50 km) to far-field (1200 ×1800 km), for evaluating the possibility of polymer build-up in the sea (Fig. 1). Several oil fields have been found to be suitable for implementing polymer flooding on the NCS (Smalley et al., 2020). We arbitrarily shortlist seven of these oil fields and simulate the repeated discharge of APAMs from these fields over approximately 10 years. The PW is discharged repeatedly after 360 days (once a year) from all fields, over 3600 days. Tables 2 and 3 summarizes the shortlisted oil fields, their coordinates, and assumed input parameters used in the simulations. The primary objective of choosing these oil fields and input parameters is to demonstrate that the method can be used to evaluate the possibility of polymer build-up. Other combinations of oil fields or input parameters can be chosen as needed.

We run four simulations with varying discharge concentrations of polymers in PW, i.e., 125, 250, 500, and 1000 mg/l from each field. The varying polymer concentrations in the PW result in different masses of polymers being discharged annually from all fields. The output data from simulations are used to extract 100- and 75-percentile concentration values at each output time step, i.e., for seven days. The reason for including 75-percentile values is to avoid extreme values that occurred in the simulations (see Section 3.2). There will be a total of about 50 concentration values for the 100 and 75 percentiles every year. Of these 50 concentration values, the highest values reported during the first and tenth years of simulation are used in a linear regression analysis against the total amount of polymer (independent variable) discharged each year. The extraction of the highest, rather than, e.g., mean, from the simulated values is done as a precaution in relation to the concentrations to be used for impact evaluations. This approach helps in evaluating the possibility of polymer concentration build-up in the sea in case of repeated discharge from multiple oil fields. The resulting regression equations can also be used to calculate an indicative highest value of the 100- and 75-percentile concentrations for other amounts of polymer discharged for future scenarios.

3. Results and discussion

3.1. Near-field simulations

EIF values are routinely used as a decision support metric to evaluate the environmental risk of different chemicals discharged along with PW into the sea (Reed and Rye, 2011). The results from the near-field simulations are assessed in terms of EIF values of two molecular weight fractions of APAMs, i.e., 200 and 8000 kDa, discharged from the Brage field (arbitrarily chosen; Section 2.3) on the NCS. The plume of PW in

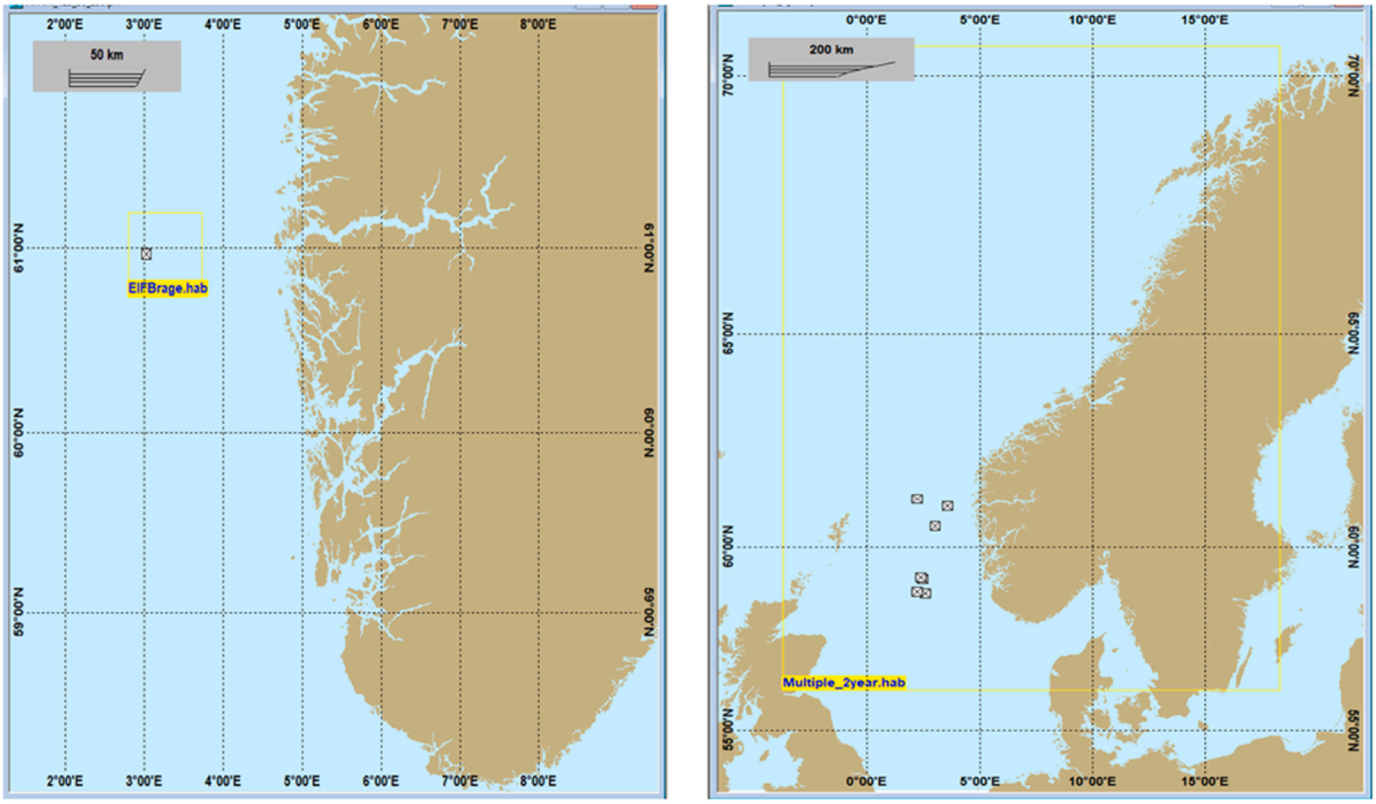

Fig. 1. Left: habitat grid for near-field simulation to assess short-term impact. Right: habitat grid for far-field simulation to evaluate the build-up of polymers. The white cross marks on both figures represent discharge sites of produced water discharges, and the yellow boundary shows the habitat grid within which the model operates.

Table 2
Information about discharge site and their coordinates.

Discharge site	Co-ordinates
Johan Sverdrup	58°48′N 2°36′E
Gullfaks	61°12′N 2°13′E
Grane	59°10′N 2°29′E
Balder field	59°13′N 2°24′E
Brage	60°32′N 3°2′E
Edvard Grieg	58°50′N 2°15′E
Fram	61°2′N 3°35′E

Table 3
Information on input parameters used in far-field simulations.

Simulation parameters	Values
Polymer concentrations	125, 250, 500 & 1000 (mg/l)
Volume of produced water discharged from each site	10,000-m^3/day
Duration of produced water discharge	8 days
Duration of simulation	3600 days
Size of habitat grid	1200 * 1800 km
Size of concentration grid	1200 * 1800 * 50 m
Concentration grid depth	500 m
Calculation time step and output time step	1 h and 7 days

Fig. 2 shows a combined effect of APAM-8000 kDa at 750 mg/l and other production chemicals discharged from the Brage field into the sea. Different colors in the figure show varying PEC/PNEC ratios in the discharged plume of PW. A PEC/PNEC ratio greater than 1 (shown in red) indicates the area of the plume that is expected to cause an environmental impact in more than 5 % of the aquatic species (and thereby a potentially unacceptable risk, as 5 % is commonly regarded as the acceptance threshold) (Karman, 1994; Reed and Rye, 2011).

Table 4 summarizes EIF contribution values at different discharge concentrations of APAMs as well as at different AFs, while Fig. 3 shows the same graphically. The EIF contribution values for 200 and 8000 kDa of APAMs are calculated at three discharge concentrations and using two sets of PNEC values, i.e., using an AF of 50 and no AF. As expected, the EIF contributions increase with increased discharge concentrations and when using larger AFs. Higher discharge concentrations increase the PEC values in the PEC/PNEC ratio, while using a higher AF makes the PNEC value lower, again increasing the PEC/PNEC ratio.

The contribution to EIF values at a discharge concentration of 250 mg/l of APAM 200 kDa (AF = 50) is estimated to be 0.378. At the same discharge concentration, the EIF contribution value of 8000 kDa APAM is estimated to be 1.77, i.e., 8000 kDa APAM causes a higher impact (and a correspondingly higher assumed risk) to the ecosystem, compared to 200 kDa APAM. Without the AFs, the difference becomes far less (0.017 vs. 0.005) but with an approximately similar ratio between them. From the experimental basis for the PNEC values (thresholds), the major cause of 8000 kDa APAMs being more toxic than those of 200 kDa is that effects are found at lower exposure concentrations than 200 kDa in early life stages of test organism *C. finmarchicus* (Farkas et al., 2020). Although the same AF (i.e., AF = 50) is used for APAM 200 and 8000 kDa, it should be noted that the effects observed from 200 kDa are based on long-term exposure studies, whereas the effects from 8000 kDa are based on acute toxicity studies. Using a higher AF for APAM 8000 kDa will result in a higher contribution to the EIF values from APAM 8000 kDa, but the conclusion regarding APAM 8000 kDa being more toxic than APAM 200 kDa will remain. Furthermore, the contribution to EIF values is significantly higher when using an AF of 50 compared to not using an AF. The use of a larger AF is typically recommended when chronic toxicity data on species from three trophic levels are not available (ECHA, 2008). Hence, further research into chronic toxicity studies on species from different trophic levels can be

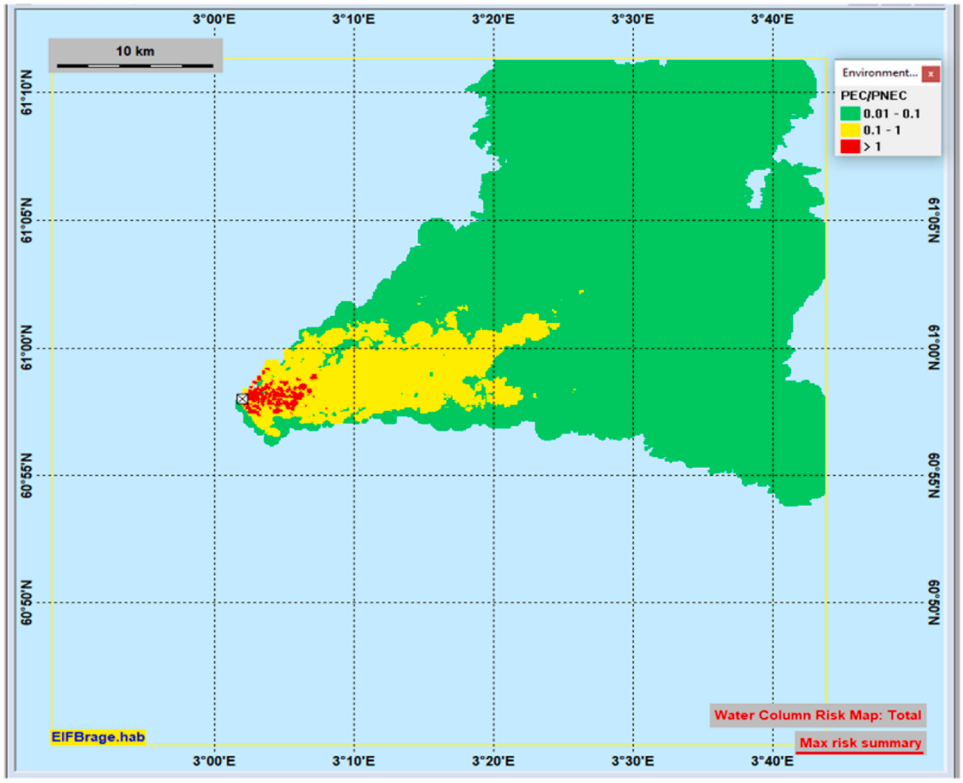

Fig. 2. Snapshot of produced water plume containing polymer and other chemicals 30 days after discharge into the sea. The red color in the plume shows the area where the PEC/PNEC ratio is greater than 1.

Table 4
Contribution to maximum Environmental Impact Factor (EIF) from different molecular weight fractions of anionic polyacrylamides.

Discharge Concentration (mg/l)	Contribution to maximum Environmental Impact Factor value			
	Assessment Factor = 50		No Assessment Factor	
	Anionic Polyacrylamide (8000 kDa) (PNEC = 2.5 mg/l)	Anionic Polyacrylamide (200 kDa) (PNEC = 10 mg/l)	Anionic Polyacrylamide (8000 kDa) (PNEC = 125 mg/l)	Anionic Polyacrylamide (200 kDa) (PNEC = 500 mg/l)
250	1.77	0.378	0.017	0.005
500	3.74	0.844	0.044	0.005
750	6.64	1.097	0.061	0.012

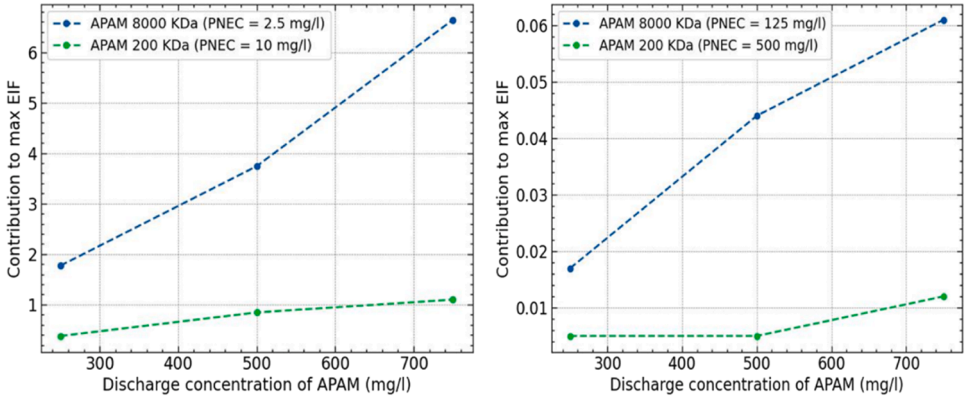

Fig. 3. Contribution to maximum Environmental Impact Factor (EIF) values from 200 and 8000 kDa molecular weight fraction of anionic polyacrylamides calculated at different discharge concentrations. Left: Environmental Impact Factor (EIF) values when assessment factor of 50 is used. Right: Environmental Impact Factor (EIF) values with no assessment factor.

helpful, allowing for the use of lower AF values, thus ensuring a more precise estimation of the contribution to EIF values from APAMs. Overall, the estimated contribution to EIF values of APAMs in this study suggests that APAMs cause low to moderate environmental impacts (and correspondingly assumed risks).

3.2. Far-field simulations

In the far-field simulations, the habitat grid is extended to cover a large area around the NCS (1200 ×1800 km). The main objective is to evaluate the possibility of an increase in concentrations in the seawater due to build-up of polymers that are repeatedly discharged from multiple oil fields over time. Fig. 4 shows the simulated concentration distribution of polymers repeatedly discharged from seven arbitrarily chosen oil fields that are suitable for implementing polymer flooding. The results show that the discharged polymer rapidly gets diluted to a concentration of a few parts per billion (PPB), with further dilution to even lower concentrations occurring over time. Most of the discharged polymer is transported northward by ocean currents and winds, eventually leaving the habitat grid over time.

A linear regression analysis is used where the highest concentration values of polymer (based on both 100- and 75-percentile values) during the first and tenth years of simulation are taken as the dependent variable, and the amount of polymer discharged each year is the independent variable (Table 5). Fig. 5 shows a summary of two linear regression plots using the highest values of 100- and 75-percentile concentrations calculated during the first and tenth years of simulation. The results show a significant difference between 100- and 75-percentile concentrations, for both the first and tenth years of simulation. The primary reason for this difference is the rapid dilution of polymers after discharge into the sea. Due to rapid dilution, a few grid cells near to the discharge point have higher concentrations, and most other cells have lower concentration values, as reflected by the 75-percentile concentration. As these near discharge point values are not representative from a long-term perspective, the 75-percentile concentrations are selected as indicators of the long-term concentrations' build-up within the simulation area. Also, a clear distinction is observed between the 75-percentile concentration values for the first and tenth years of simulation, i.e., the 75-percentile values during the tenth year of simulation are significantly lower than the values calculated for the first year of simulation. This result indicates that there is no build-up of polymer concentrations in the simulation area from repeated discharge; in fact, there is further dilution as polymer spreads across the habitat grid over time before eventually leaving the grid. There is no reason to believe that the values may be higher anywhere outside the simulation area than inside it.

$$C_{1y,100pct} = 1.78{\cdot}10^{-4}x - 1.73{\cdot}10^{-4} \quad (1)$$

$$C_{1y,75pct} = 0.02x - 0.14 \quad (2)$$

$$C_{10y,100pct} = 1.54{\cdot}10^{-6}x + 8.91{\cdot}10^{-7} \quad (3)$$

$$C_{10y,75pct} = 0.04x - 0.42 \quad (4)$$

Eqs. (1) and (2) are from the regression analyses based on 100- and 75-percentile concentrations, respectively, during the first year of simulation, while Eqs. (3) and (4) are based on 100- and 75-percentile concentrations, respectively, during the tenth year of simulation. These equations can be used to calculate an indicative value of 100- and 75-percentile concentrations for any other amount of polymer discharged annually from other oil fields on the NCS. The result of such analysis will assume that parameters such as duration of discharge, locations of discharge sites, and ocean currents are approximately similar to those used in this study. The input values of the above-mentioned parameters used in the far-field simulations are typical expected values. Hence, such analysis can be relevant and useful in getting an indication of concentration values for future discharge scenarios.

Fig. 5 shows that the simulated concentration values for the 100 percentiles during the first and tenth years are approximately similar and are in the range of a few PPB. In comparison, the lowest reported toxicity value is about 125 mg/l or approximately 125,000 PPB with no AF and 2.5 mg/l or 2500 PPB when an AF equal to 50 is used. Hence,

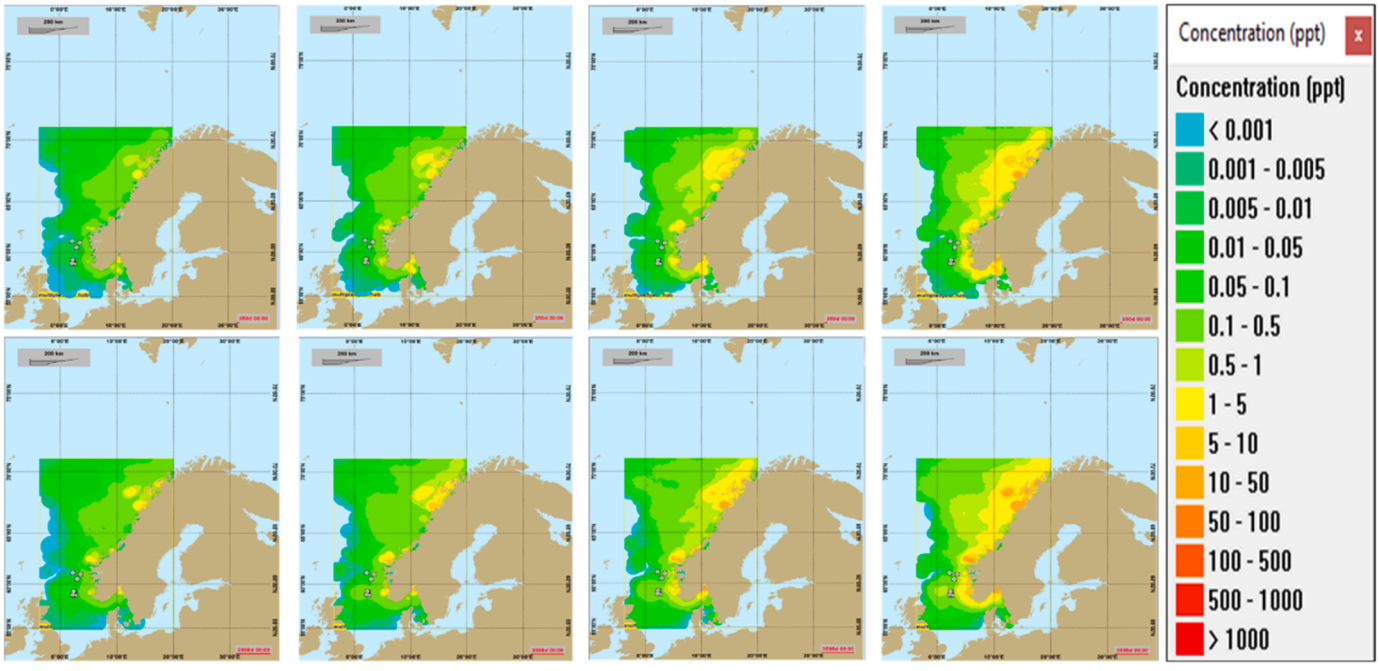

Fig. 4. Simulated concentration distribution of polymers repeatedly discharged (after approx. 1 year) from multiple oil fields over an approx. 10-year period. The four figures on the top show a snapshot of concentration distribution after approx. 1 year, while the bottom four figures show the same after approx. 10 years. Figures from left to right show increased discharged concentration of polymers (as 125, 250, 500, and 1000 mg/l). The color code in the figure represents concentration distribution in parts per trillion (PPT).

Table 5
Summary of extracted data from far-field simulations used to establish a relationship between the amount of polymer discharged each year and the concentration of polymer.

Simulation	Volume of PW discharged from each field per year (m^3)	Total volume of PW from 7 fields over 8 days per year (m^3)	Discharge concentration (mg/l)	Mass of polymer discharged per year (Tons/year)	Concentration calculated after first year of simulation (PPB)		Concentration calculated after tenth year of simulation (PPB)	
					100 percentile	75 percentile	100 percentile	75 percentile
1	10,000	560,000	125	70	1.7	0.012	3.2	0.0001
2	10,000	560,000	250	140	3.3	0.025	6.4	0.0002
3	10,000	560,000	500	280	6.7	0.048	12.2	0.0004
4	10,000	560,000	1000	560	13	0.10	26.7	0.0008

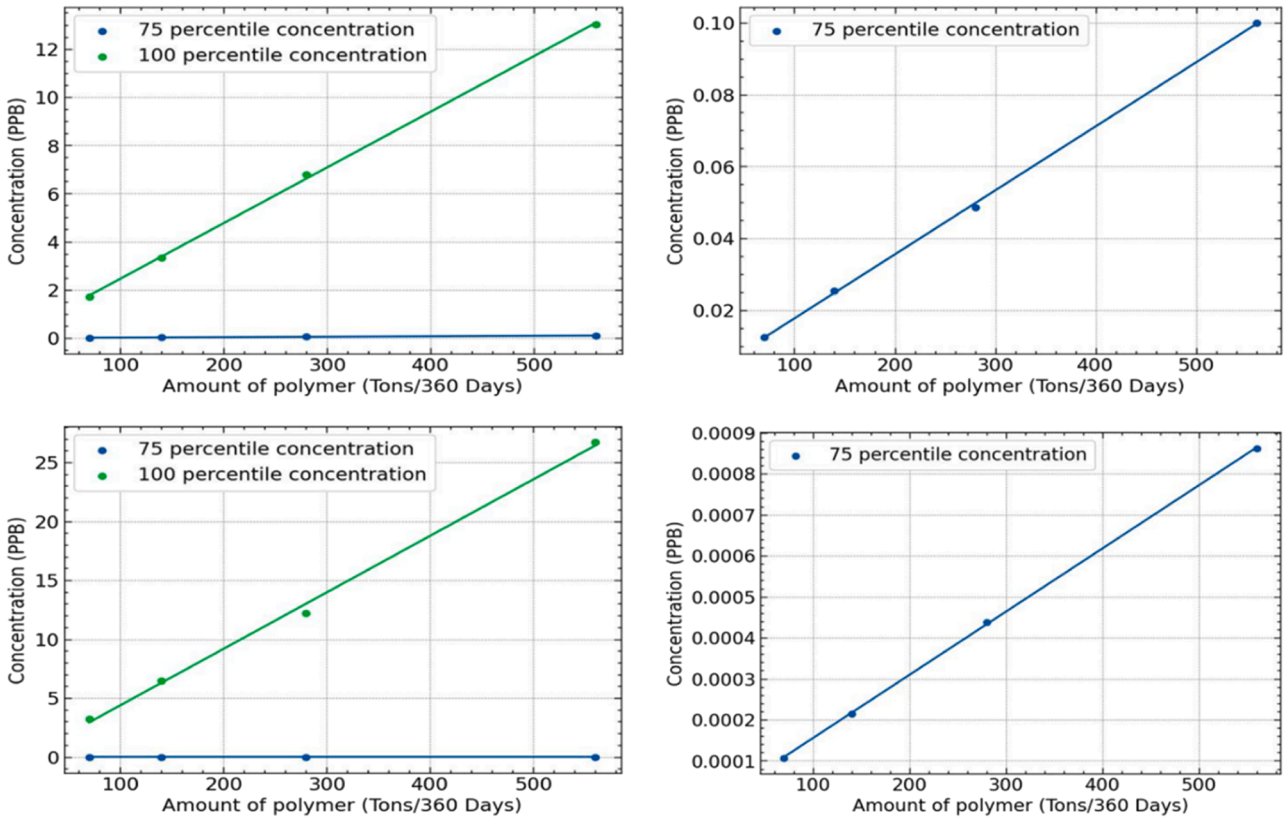

Fig. 5. Linear regression results for polymer concentration against the amount of polymer discharged each year. Top left: linear regression for the mass of polymer discharged each year and extracted highest values of 100- and 75-percentile concentrations during the first year of simulation. Bottom left: similar linear regression as top left but for concentration values extracted during the tenth year of simulation. Diagrams on the right side show the 75-percentile concentrations from the left-side diagram plotted on different scales.

there is a considerable margin of safety, i.e., even with a higher amount of polymer discharged each year from multiple discharge sites, the concentration values on the NCS are not expected to become high enough to cause any direct harmful effects on aquatic species. It should be noted that, in Fig. 5, some areas of high concentrations appear along the coast of Norway compared to the adjacent areas. These concentration values are captured when using the highest values of 100-percentile concentration; however, there are reasons to believe that these values are due to artifacts in the model simulations. The polymers are represented as dissolved substances in the model and should not build up in the case of eddies or similar current patterns. Hence, the 75-percentile concentration values are chosen in addition to the 100 percentile ones to -avoid the analysis being based on extreme values that may not be reflective of a larger area on the NCS.

It is important to note that the concentration values will vary with the spatial resolution. The resolution used to calculate concentrations in the far-field simulations (1200 ×1800 ×50 km) is lower than in near-field simulations (100 ×100 ×10 km). This is because of a software model constraint limited to 1000 cells within the habitat grid. We ran a set of simulations with varying spatial resolutions to evaluate the change in concentration values. This showed that the calculation of concentration values varied with the spatial resolution only for the duration of the discharge. This was due to unrepresentative in- and out-transport values in the large grid cells for each time step, as long as the concentration gradient was large. Once the discharge stopped, the concentration values for different spatial resolutions were approximately similar, reflecting a fairly constant transport of polymer mass at relatively even concentrations in the sea, due to ocean currents, winds, and dilution. Further details about these simulations are available in the supplementary information.

Even though the estimated EIF values indicate that synthetic polymers may have relatively low to moderate environmental effects on aquatic species, there remains uncertainty about this result. The discharged polymers are expected to undergo degradation and the primary

degradation is anticipated to involve the presence of reactive oxygen species (ROS) originating from both biological and photocatalytic sources (Nomi et al., 2015; Ramsden and McKay, 1986). The degradation of polymers will result in the formation of intermediate polymer compounds, and the toxicity of these intermediate compounds remains uncertain. While some studies have suggested a potential connection between polymer chain length and toxicity (Bolto and Gregory, 2007), others have not established a direct correlation (Beim and Beim, 1994; Hall and Mirenda, 1991). Therefore, further research is required to gain better understanding of the relationship between polymer chain characteristics and toxicity.

In addition to the toxicity concerns, limited research has explored other aspects of the fate and environmental transport of synthetic polymers in the marine environment (Brakstad et al., 2020, 2021). These studies primarily investigate the interactions and attachments of synthetic polymers to both living and deceased algal materials as well as mineral particles. The findings from these studies indicate that, under typical discharge concentrations, synthetic polymers are not expected to significantly interact or attach to algal materials or mineral particles. Consequently, it is indicated that polymer will not undergo sedimentation after discharge but will predominantly be transported by water currents and gradually degrade within the water column. Further studies will be needed to verify if this will be the case after long term in the sea. The primary mechanism of this degradation is expected to be the ROS originating from biological and photocatalytic sources.

4. Conclusion

In this study, we assess the potential environmental impact that may increase the environmental risk of discharging synthetic polymers into the marine environment on the NCS. The assessment is based on using the DREAM model to run short-time/small-scale/near-field and long-time/large-scale/far-field simulations of discharging polymers on the NCS. The near-field simulations are used to assess short-term impact in terms of EIF values of APAM-200 kDa and 8000 kDa. The results indicate that APAM-8000 kDa will have a higher potential impact than APAM-200 kDa at similar discharge concentrations. Overall, synthetic polymers can be expected to cause a lower environmental impact, although uncertainties still apply, due to the complexity of the issue and the limitation in relevant data for such complex analysis.

In the far-field simulations, the possibility of build-up in seawater of polymers repeatedly discharged from multiple oil fields is assessed. The simulation results show that synthetic polymers will be transported by ocean currents/winds and are not expected to build up to concentration values implying harmful impacts within the grid used in the simulation. In addition, linear regression is used to establish a relationship between the annual amount of polymer released and the resulting extracted highest values of the 75-percentile concentrations during the first and tenth years of discharge. The results from such analysis show a considerable margin of safety between expected concentrations and concentrations at which harmful effects on relevant aquatic species are observed. Furthermore, the available regression equations can be used to indicate the highest values of the 75-percentile concentrations for future release scenarios.

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CRediT authorship contribution statement

Mehul Vora: Investigation, Data curation, Formal analysis, Writing – original draft. **Steinar Sanni:** Conceptualization, Formal analysis, Writing – review & editing. **Emily Lyng:** Formal analysis, Writing – review & editing. **Roger Flage:** Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mehul Vora reports financial support was provided by Norges Forskiningsrad.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2023.103334.

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