OSPAR COMMISSION

Modelling and assessment of additional concentrations of NORM in seawater from discharges of produced water from the offshore oil and gas sector in the North-East Atlantic

Radioactive Substances Series

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Modelling and assessment of additional concentrations of NORM in seawater from discharges of produced water from the offshore oil and gas sector in the North-East Atlantic

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

Acknowledgments

This report has been produced by the Intersessional Correspondence Group (ICG), of the Radioactive Substances Committee (RSC)[1], on 'the modelling of additional concentrations of Naturally Occurring Radioactive Material (NORM) in seawater from discharges of produced water from the offshore oil and gas sector', referred to as ICG-MOD.

[1] https://www.ospar.org/work-areas/rsc

Contents

*Annexes A and B are provided as separate documents

Executive Summary

This report has been produced by the Intersessional Correspondence Group (ICG), of the Radioactive Substances Committee (RSC)[2], on 'the modelling of additional concentrations of Naturally Occurring Radioactive Material (NORM) in seawater from discharges of produced water from the offshore oil and gas sector', referred to as ICG-MOD.

ICG-MOD was established to undertake modelling of discharges of produced water from oil and gas installations to estimate the resulting additional concentrations of naturally occurring radioactive materials (NORM) in seawater. A modelling approach was necessary because it is not possible to measure additional concentrations of NORM in seawater from discharges of produced water, above natural background concentrations, beyond the immediate vicinity of any discharge point by analytical means (i.e. sampling of seawater).

Two forms of modelling were undertaken: (a) so called near-field modelling to estimate additional concentrations of NORM in the immediate vicinity of installations discharging produced water; and (b) far-field modelling to derive additional concentrations of NORM in seawater and sediments, from discharges of produced water, across the OSPAR Maritime Area.

The results of the near-field modelling represent localised and transient conditions and are not appropriate for consideration of trends over wide areas or extended periods. However, examples of near-field modelling of dilution at 500 m from discharging installations are also presented and compared with the EACs for completeness and in the interests of transparency.

The additional concentrations of naturally occurring radionuclides in seawater resulting from discharges of produced water from oil and gas installations in the OSPAR Maritime Area were evaluated using the far-field compartmental numerical modelling approach. These values were compared with indicative background values to evaluate whether total concentrations, including this component, could be considered to be near background values (the first objective of the OSPAR RSS under the NEAES 2010 – 2020). In all cases, modelled additional concentrations were far less than the variations in background levels and far lower than typical low-end background levels. These values were also less than the uncertainties in measurements of background. In practice, this means that any additional concentrations would likely be indistinguishable from background levels measured by routine analytical techniques for environmental monitoring purposes.

The radiological impact of the modelled additional concentrations was also evaluated, using reference environmental concentrations, established by OSPAR RSC for this purpose. In all cases the annual doses from the additional concentrations of these indicator radionuclides in seawater would be below the trivial annual dose of 10 µSv and a small fraction of the concentrations at which effects on biota have been observed. These levels would not result in any radiological impact to humans or the marine environment.

The comparisons with background levels, taken together with assessment on radiological impact, indicate that it is reasonable to consider, for seawater, that the ultimate aim of 'total environmental concentrations of naturally radionuclides are near background levels' is likely to have been achieved.

[2] https://www.ospar.org/work-areas/rsc

Récapitulatif

Le présent rapport a été établi par le groupe intersessionnel par correspondance (ICG) du Comité des substances radioactives (RSC) [3] sur la modélisation des concentrations additionnelles de matériaux radioactifs naturels (NORM) dans l'eau de mer provenant des rejets de l'eau de production par le secteur pétrolier et gazier offshore, appelé ICG-MOD.

L'ICG-MOD a été créé pour effectuer la modélisation des rejets de l'eaux de production provenant des installations pétrolières et gazières afin d'estimer les concentrations additionnelles de matériaux radioactifs naturels (NORM) dans l'eau de mer. Une approche de modélisation était nécessaire car il n'est pas possible de mesurer les concentrations additionnelles de NORM dans l'eau de mer provenant des rejets d'eau de production, au-dessus des concentrations de fond naturelles, au-delà du voisinage immédiat de tout point de rejet par des moyens analytiques (c'est-à-dire l'échantillonnage de l'eau de mer).

Deux formes de modélisation ont été effectuées : (a) modélisation en champ proche pour estimer les concentrations additionnelles de NORM dans le voisinage immédiat des installations rejetant de l'eau de production ; et (b) modélisation en champ lointain pour dériver les concentrations additionnelles de NORM dans l'eau de mer et les sédiments, à partir des rejets d'eau de production, dans toute la zone maritime OSPAR.

Les résultats de la modélisation en champ proche représentent des conditions localisées et transitoires et ne sont pas appropriés pour l'examen des tendances sur de vastes zones ou des périodes prolongées. Toutefois, des exemples de modélisation en champ proche de la dilution à 500 m des installations de rejet sont également présentés et comparés aux EAC (critère d'évaluation environnementale) pour des raisons d'exhaustivité et dans un souci de transparence.

Les concentrations additionnelles en radionucléides naturels dans l'eau de mer résultant des rejets d'eau de production des installations pétrolières et gazières dans la zone maritime OSPAR ont été évaluées à l'aide de l'approche de modélisation numérique compartimentale en champ lointain. Ces valeurs ont été comparées aux valeurs de fond indicatives afin d'évaluer si les teneurs totales, y compris cette composante, pouvaient être considérées comme proches des valeurs de fond (premier objectif de la Stratégie substances radioactives dans le cadre de la Stratégie pour le milieu marin de l'Atlantique Nord-Est 2010 - 2020). Dans tous les cas, les concentrations supplémentaires modélisées étaient bien inférieures aux variations des niveaux de fond et bien inférieures aux niveaux de fond bas typiques. Ces valeurs étaient également inférieures aux incertitudes des mesures des niveaux de fond. Dans la pratique, cela signifie que toute concentration supplémentaire serait probablement impossible à distinguer des niveaux de fond mesurés par des techniques analytiques de routine à des fins de surveillance environnementale.

L'impact radiologique des concentrations additionnelles modélisées a également été évaluée, à l'aide des de concentrations environnementales de référence, établies par le RSC d'OSPAR à cette fin. Dans tous les cas, les doses annuelles dues aux concentrations supplémentaires de ces radionucléides indicateurs dans l'eau de mer seraient inférieures à la dose annuelle triviale de 10 µSv et à une petite fraction des concentrations auxquelles des effets sur le biote ont été observés. Ces niveaux n'entraîneraient aucun impact radiologique pour l'homme ou le milieu marin.

Les comparaisons avec les niveaux de fond, ainsi que l'évaluation de l'impact radiologique, indiquent qu'il est raisonnable de considérer, pour l'eau de mer, que l'objectif ultime, à savoir que les concentrations totales de radionucléides naturels dans l'environnement soient proches des niveaux de fond, a probablement été atteint.

[3] https://www.ospar.org/work-areas/rsc

1 Introduction

1.1 Background

This report has been produced by the Intersessional Correspondence Group (ICG), of the Radioactive Substances Committee (RSC)[4], on 'the modelling of additional concentrations of Naturally Occurring Radioactive Material (NORM) in seawater from discharges of produced water from the offshore oil and gas sector', referred to as ICG-MOD.

The aim of this report is to document the work undertaken by ICG-MOD, primarily to provide input to the Fifth Periodic Evaluation of progress towards meeting the objectives of the North-East Atlantic Environment Strategy (NEAS) for the period 2010-2020 for radioactive substances (subsequently referred to as NEAS 2010 - 2020) namely:

> *"1.1 The OSPAR Commission's strategic objective with regard to radioactive substances is to prevent pollution of the OSPAR maritime area from ionising radiation through progressive and substantial reductions of discharges, emissions and losses of radioactive substances, with the ultimate aim of concentrations in the environment near background values for naturally occurring radioactive substances and close to zero for artificial radioactive substances. In achieving this objective the following issues should, inter alia, be taken into account: a. radiological impacts on man and biota; b. legitimate uses of the sea; c. technical feasibility.*
>
> *1.2 The Radioactive Substances Strategy will be implemented progressively by making every endeavour, through appropriate actions and measures to ensure that by the year 2020 discharges, emissions and losses of radioactive substances are reduced to levels where the additional concentrations in the marine environment above historic levels, resulting from such discharges, emissions and losses, are close to zero."*

One of the main aims of this assessment was to determine progress towards achieving the "…ultimate aim of concentrations in the environment near background values for naturally occurring radioactive substances…".

The main source of discharges of radionuclides to the OSPAR marine environment from the oil and gas sub-sector result from discharges of produced water. The radioactive content of produced water arises from naturally occurring radionuclides, and includes Pb-210, Ra-226 and Ra-228. Contracting Parties have reported discharge data on these indicator radionuclides for the oil and gas sub-sector since 2005[5]. This, and more detailed installation-specific information, was used to model the additional concentrations of these radionuclides and their progeny in seawater and sediments.

The assessment of whether the concentrations of artificial radionuclides are "close to zero" or close to "historic levels" is the subject of another RSC ICG (ICG-CTZ), and beyond the scope of this report. ICG-MOD and ICG-CTZ have worked together to ensure that the relevant assessments are consistent, to the extent possible. However, for artificial radionuclides, it is possible to base such an analyses on analytical methods (i.e. measurements of seawater) due to the availability of suitable analytical methods and extensive

[4] https://www.ospar.org/work-areas/rsc

[5] Additionally, RSC has estimated values for total alpha and total beta (excluding tritium) based on reported measured values for Pb-210, Ra-226 and Ra-228 using formulae that take into account contributions from key radioactive daughter products.

historical dataset. As a consequence, statistical analysis methods have been developed for artificial radionuclides, as described elsewhere (ICG-CTZ report/agreement). This approach is not possible for NORM; additional concentrations of NORM arising from discharges of produced water above natural background levels can only be measured in the immediate vicinity of discharge points. In addition, there are insufficient data available on additional concentrations in seawater to allow statistical analysis, or to evaluate 'historic levels', as for artificial radionuclides. Additional concentrations representative of those in the OSPAR maritime region have therefore been estimated by a numerical modelling, on the basis of reported annual discharge data. Such data have only been available since 2005, which also makes it difficult to undertake a meaningful evaluation of 'historic levels' for NORM, based on modelling. In this case, the evaluation of progress towards the NEAS 2010 - 2020 objectives is therefore focused on the first objective or 'ultimate aim', rather than the second objective.

1.2 Scope of Report

This report focuses on modelling approaches for discharges of naturally occurring radioactive materials (NORM), in produced water from the oil and gas sector. One of the main aims was to assess whether additional concentrations of NORM related radionuclides in the OSPAR Maritime Area are "near background values", since it was determined that there were insufficient data available to make a meaningful assessment of 'historic levels'. This report also includes a screening assessment of radiological impact of additional concentrations of NORM in seawater, using Environmental Assessment Criteria derived by OSPAR RSC for this purpose, also referred to reference activity concentrations (Cref). The results presented in this report are therefore considered to be appropriate for assessing progress against the the objectives for OSPAR RSS, and therefore as input to the Fifth Periodic Evaluation. Trends in discharges of NORM are also considered as part of the Fifth Periodic Evaluation but are not included in detail in this report.

The report compiles information from various documents presented to the OSPAR RSC in various status and project reports. The focus is on far-field modelling considering the North-East Atlantic Maritime Area. Information on near-field modelling of dilution at a distance of 500 m from representative discharging facilities is also presented, for information and in the interests of transparency.

1.3 Structure of the report

The remainder of this report is structured as follows:

- An overview of the assessment approach is provided in Section 2.
- A description of the derivation of key assessment data, including discharge data and representative background levels, used is provided in Section 3.
- Far-field modelling approach and results are provided in Section 4.
- Near-field modelling approach and results are provided in Section 5.
- Summary and concluding points are provided in Section 6 and references are listed in Section 7.

This report is then supported by two appendices:

- Appendix A describes the far-field modelling of activity concentrations in bed sediment and a compilation of the associated results.
- Appendix B provides a screening level radiological assessment of concentrations in the immediate vicinity of a range of installations, using relationships between discharge and concentrations derived from the near-field modelling approach.

Two reports are provided as annexes to this report, which describe the near-field modelling approach and results in more detail.

2 Overview of the assessment methodology

Recognizing that it is not possible to measure additional concentrations of NORM radionuclides, above background levels, except in the immediate vicinity of discharging installations, additional concentrations in seawater were derived by means of numerical modelling, using discharge data.

Two forms of modelling were undertaken to provide information on additional concentrations of naturally occurring radionuclides in seawater, resulting from discharges of produced water, on different temporal and spatial scales.

Concentrations in the immediate vicinity of discharging installations are highly variable, both temporally and spatially. Information on the localized situation (the near-field) is a factor in installation-specific decision making, for all types of installation, notably including Contracting Parties' (CPs) regulatory practices. In the interests of transparency, CPs worked together to evaluate and present consistent information on additional concentrations in the immediate vicinity of selected discharging installations.

The information from near-field modelling is not, however, indicative of the situation over wider areas or for extended durations. Another approach, referred to as far-field modelling, was therefore applied to evaluate additional concentrations of naturally occurring radioactive substances in the OSPAR Maritime Area. These data were used to assess progress towards the NAEAS 2010 – 2020 objectives with respect to radioactive substances. It was determined that there were insufficient environmental monitoring and discharge data available to make a meaningful assessment of 'historic levels' for NORM radionuclides. Consequently, the focus of this work was to determine whether the additional concentrations in the OSPAR Maritime Area may be considered to be "near background values". A screening evaluation of the associated radiological impact was also performed using the OSPAR RSC Environmental Assessment Criteria or reference activity concentrations (Crefs), which were derived for this purpose.

The estimated additional concentrations of the indicator radionuclides, Pb-210, Ra-226 and Ra-228, in filtered seawater were chosen as the primary basis for assessment.

Seabed sediment is not an OSPAR indicator compartment: measured data for sediments are not generally useful for long-term trend analysis due to the high level of variation, arising from the nature and properties of sediments. However, given that the ultimate fate of the NORM indicator radionuclides in produced water discharges will be accumulation in seabed sediment, additional concentrations in bed sediments in the OSPAR Maritime Area were also estimated by numerical modelling and are included in Appendix A of this report, for completeness and to allow these data to be considered further by RSC, as appropriate[6].

It would also be possible to derive additional concentrations in other environmental compartments by modelling, e.g. fish. However, these values would be derived directly from the estimated concentrations in seawater or sediments and would therefore follow the same numerical trends as the data for seawater and sediments such that of the analysis these data would not provide useful additional information. Furthermore, the radiological impact associated with these compartments is effectively included in the EAC methodology.

The cumulative impact of continuing discharges on additional concentrations in the OSPAR Maritime Area was also investigated using far-field modelling of unit discharges, as described in more detail in Section 4.

[6] Near-field estimations of additional seawater concentrations were deliberately conservative and assumed no losses to sediment.

Thus, two forms of modelling were undertaken with different objectives, the key features of these models and their application are summarized below:

1. The **near-field modelling** of discharges of indicator nuclides in produced water from a representative selection of production platforms and modelling of the dilution in the immediate vicinity of these installations, from which seawater concentrations from such discharges were derived; and
2. **Far-field modelling** to derive additional concentrations of NORM above background in seawater from discharges of produced water from all platforms across the OSPAR Maritime Area.

The results of the near-field modelling represent localised and transient conditions and are presented to ensure that near-field impacts are understood and documented, and in the interests of transparency. The approach adopted for near-field modelling is illustrated in Fig. 1. More details on the near-field modelling approach are provided in Section 5 and in the annexes to this report.

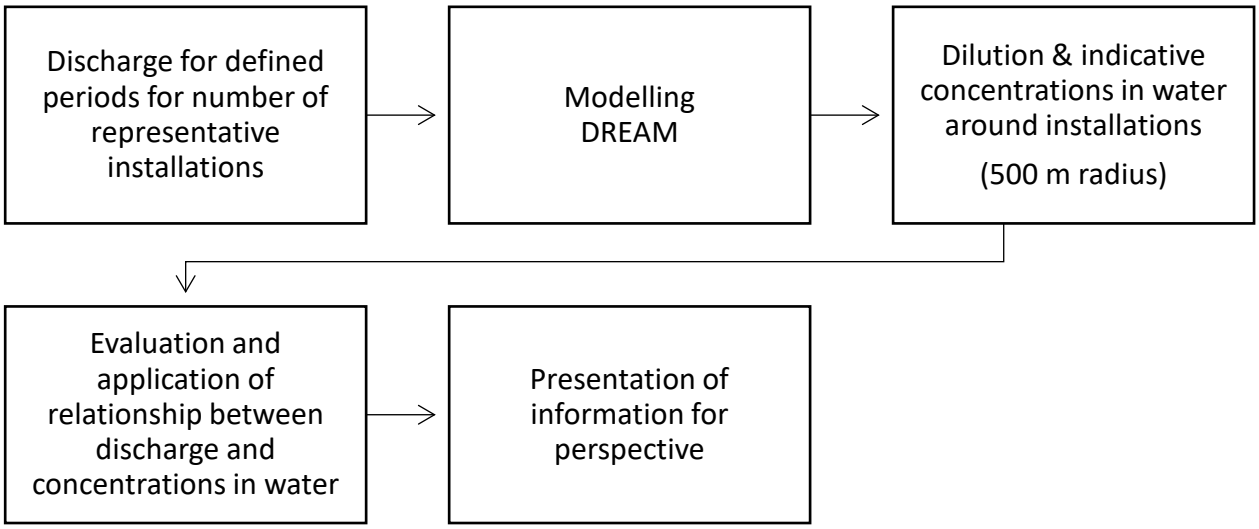

Fig. 1. Near-field modelling approach and its application

The far-field modelling exercise provides the basis for assessing cumulative additional concentrations over wide geographical areas, and therefore for assessing progress against the objectives of the OSPAR RSS. These results are therefore appropriate as inputs to the Fifth Periodic Evaluation. This approach is therefore described in more detail in this report. Schematic illustrations of the overall approach is presented in Fig 2.

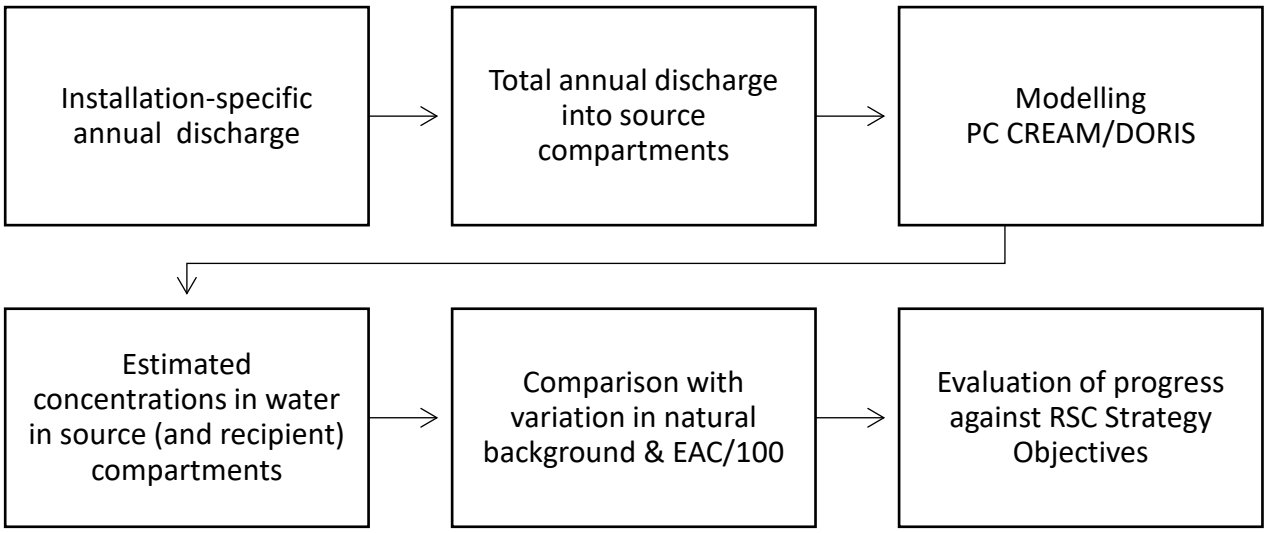

Fig. 2. Far-field modelling approach and its application

The approaches are described in more detail in Sections 4 and 5. The far-field assessment is the focus for the report and is therefore presented first (Section 4).

3 Assessment data

As indicated in the previous section, one of the main purposes of this report is to consider progress against the objectives of the OPSAR RSS, under the North-East Atlantic Environment Strategy 2010 – 2020, which are relevant to NORM. The first objective relates to the "ultimate aim that concentrations in the environment are near background values for naturally occurring radioactive substances". The second objective is that by 2020, additional concentrations [of radionuclides] in the marine environment above historic levels are close to zero. Unfortunately, there are insufficient data to evaluate historic levels so, it is not possible to directly assess progress against the second objective, unlike the case for artificial radionuclides. Therefore, this assessment is focussed on the first objective of concentrations in the environment being near background values.

In order to determine if concentrations are 'near background values', it is necessary to establish the background concentrations of the different natural radionuclides and also to establish what should be interpreted as 'near'. The RSC has decided that if the environmental concentrations, including the additional contribution from discharges of produced water, falls within the natural variability of the natural radionuclide in question it should be considered near background.

This assessment also includes a screening analysis of the radiological impact of the additional concentrations, using an agreed OSPAR methodology. This involves comparison with a fraction of the activity concentrations corresponding to public health and environmental criteria.

This assessment is therefore dependent on three major data sets, which are discussed in turn below, namely:

- Discharges of produced water from oil and gas platforms in the OSPAR Maritime Area;
- Estimated 'background' values of naturally occurring radionuclides in seawater, including indications of the variability and uncertainty associated with these values;
- The environmental activity concentrations corresponding to public health and environmental criteria.

The derivation and application of these data sets is described in the following sections.

3.1 Discharge data

The OSPAR Contracting Parties (CPs) with offshore installations in their territories were identified using information available in the OSPAR Data and Information Management System (ODIMS).

The relevant CPs were contacted and requested to indicate which installations had discharged produced water at any time since discharge reporting to OSPAR commenced in 2006[7]. For those installations that had discharged, CPs were requested to provide data on the volume of produced water discharged (m^3) and the total activity (MBq) of lead-210 (Pb-210), radium-226 (Ra-226); and radium-228 (Ra-228) discharged each year. Installation-specific information was thus collated for the period 2006 - 2015 for a total of 180 installations, from the following CPs: United Kingdom, Norway, Denmark, Netherlands, Germany and Ireland. These data are included in ODIMS (to be confirmed).

For the purposes of the far-field modelling exercise, the total annual discharges into different model compartments were calculated. These compartments were broadly representative of OSPAR Regions, although with some differences in spatial extent, as discussed in more detail in Section 4.

[7] Discharge reporting began in 2006 under OSPAR Agreement 2005-07 (now replaced by Agreement 2013-11). This work was undertaken during the period 2016 – 2017, such that 2015 was the most year for which recent discharge data were available at the time of assessment.

The modelling exercise was undertaken for discharges during the period 2006 – 2015. Analysis of subsequent discharge data [Ref: non-nuclear discharge report] demonstrates that discharges of produced water in the OSPAR Maritime Area have either reduced or remained approximately the same. It is therefore reasonable to assume that the results of this assessment will also be valid for the period up to 2019, and appropriate for input to the Fifth Periodic Evaluation. Furthermore, additional analyses indicated that the cumulative effects of long-term discharges are unlikely to influence this conclusion, as described in Section 4. The highest additional concentrations, in the compartments in which installations are located, are representative of steady state conditions. The additional activity concentrations of NORM radionuclides in these compartments can therefore also be considered to be applicable to the period covered by the Fifth Periodic Evaluation.

3.2 Background concentrations of naturally occurring radionuclides

The background concentrations (i.e. that unaffected by human activities) of naturally occurring radionuclides in the marine environment are influenced by the source of the radionuclide in question, by the radionuclides half-life and chemical properties and by various biological, geological, chemical and oceanographic processes. Accordingly, there is a not a single background concentration for each natural radionuclide, rather natural background concentrations vary both spatially and temporally.

The following text examines the sources and fates of the different indicator nuclides along with literature and OSPAR monitoring data to determine the magnitude and variability of the background.

The OSPAR monitoring database includes natural radionuclide measurements from 1996 to present day. However, as discharges of radionuclides in produced water from the oil and gas industry have been taking place in the OSPAR maritime area for over 50 years, it is possible that measurements taken in this period could be affected by human activities rather than reflect natural background. Part of the evaluation described below was therefore to determine whether the OSPAR measurement data, including these additional contributions, may be considered to be consistent with background levels.

3.2.1 Radium

The principal sources of radium to the marine environment are wash-off from land and dissolution from seabed sediments (radium being more soluble than its parent element thorium). The main mechanism of removal are radioactive decay and particle scavenging. Reflecting this, in general, concentrations of radium can be enriched by over on order of magnitude in estuaries and coastal waters compared to the open-ocean [see IAEA TRS476 environmental behaviour of radium]. Away from the continental shelf, surface waters have a lower concentration than deep waters, which are influenced by dissolution from sediments.

Several, global oceanographic scientific programmes have measured the radium-226, and radium-228 in the World's oceans [REF Geosecs and Geotracers]. These show that in the Atlantic Ocean the concentration of radium-226 is 1.3 mBq/l and radium-228 is 0.18 mBq/l with the concentrations varying around 10%. Although the majority of these measurements were not taken in the OSPAR maritime area they represent a useful lower bound for background concentration.

There are a large number of radium measurements in the OSPAR monitoring database; the radium-226 and radium-228 data are summarised in Tables 8 and 9 respectively. The data is presented for each region and as combined data set. It can be seen that there is an unequal distribution of data, with the majority of the data related to RSC sub-regions 8 and 9. Examination of the data, shows that for both radium-226 and radium-228 exhibit a high degree of variability with maximum and minimum values within sub-regions, varying by more than two orders of magnitude. As expected, these values are somewhat higher than concentrations measured in the open ocean.

Tables 1 and 2, include the minimum, mean and other percentile values for each sub-region and for the OSPAR maritime area as a whole.

The reason for the highest measurements has not been investigated in detail as part of this assessment. However, some of the higher values are suspected to be associated with higher suspended loads of sediment at the time of sample collection, and therefore may represent natural variability. Other possibilities include enhanced input from human activities such as phospogypsum processing. Nevertheless, the similarity between the Geosecs data, which predates oil and gas exploitation in OSPAR maritime area, and the Geotracers data provides reassurance that the measurements in the OSPAR area are unaffected by human activity and that these ambient values can be considered as background values.

Table 1. Statistics for the activity concentrations of radium-226 radionuclides measured in seawater in OSPAR sub-regions and for the OSPAR maritime area (mBq/l)

OSPAR Sub-region	Number of measurements	Activity concentration in seawater (mBq/l)					
	N	min	Max	Mean	Median	75%ile	95%ile
R8	761	0.4 ± 0.16	530 ± 100	7.3	4.3	7.0	18
R9	107	1.1 ± 0.11	55.3 ± 22.1	6.9	4.6	6.1	14
R10	63	0.9 ± 0.12	2.9 ± 0.29	1.5	1.5	1.7	2.5
R11	6	1.2 ± 0.12	5.1 ± 0.51	2.5			
R13	11	0.50 ± 0.05	2.7 ± 0.22	2.7			
R14	14	0.30 ±0.03	1.9 ± 0.20	1.4			
R15	6	0.26 ± 0.03	2.1 ± 0.20	1.7			
All data	968	0.4 ± 0.16	530 ± 100	6.6	4.0	6.3	15.3

Table 2. Statistics for the activity concentrations of radium-228 radionuclides measured in seawater OSPAR sub-regions and for the OSPAR maritime area (mBq/l)

OSPAR Sub-region	Number of measurements	Activity concentration in seawater (mBq/l)					
	N	min	Max	Mean	Median	75%ile	95%ile
R8	245	0.2 ± 0.08	36 ± 14	2.6	1.9	3.3	6.4
R9	26	0.47±0.18	24 ± 9.6	3.4			
R10	8	0.12±0.012	3.1 ± 0.31	1.1			
R11	No data						
R13	4	0.12±0.012	3.0±0.19	1.1			
R14	3	0.55±0.17	0.63±0.06	0.58			
R15	No data						
All data	286	0.12±0.012	36 ± 14	19			

Taking all of this information together, A lower bound background value of approximately 1 mBq /l is consistent with the open ocean values of 1.3 mB/l, which the lower end of environmental concentrations. Only 47 measurements (4.9% of the total) were lower than this value, indicating that it may be useful as a lower bound for background in the OSPAR maritime area, referred to below as the typical low-end background value for this radionuclide.

Typical high-end background values have been evaluated using monitoring data reported to OSPAR. The range of monitoring data reported to OSPAR has been compared with and were found to be consistent

with those from wider global measurement programmes, providing confidence that these data are representative of expected background levels. For Ra-226 and Ra-228, typical high-end values were chosen, representing the 75th percentile of all the monitoring data reported to OSPAR for these radionuclides. The difference between low and high-end values (the range) was then considered to be a measure of the variability of background levels for each naturally occurring radionuclide.

Tables 1 and 2 also include information on the uncertainties associated with the measurement values. These vary depending on the methods applied, calculation approach and the basis for reporting. However, it can be seen from these data that the uncertainty in measurement is typically of the order of 10%, although much greater uncertainties have been reported in some cases. This implies that, if additional concentrations are less than around 10%, these values would not be distinguishable from the natural background by measurement means.

3.2.2 Lead-210 and polonium 210

The principal sources of lead-210 and polonium 210 to the marine environment are deposition in rainwater (the lead and polonium originating from the decay of radon-222) and wash off from land. Lead and polonium are less soluble than radium meaning dissolution from sediments is not a significant source. The main removal mechanisms are radioactive decay and particle scavenging. Given the land-based sources and relatively short half-life of these nuclides, concentrations of lead-210 and polonium-210 are highest in coastal and surface ocean waters. Typical concentrations in the North Sea have been estimated to be 0.8 Bq/l for both nuclides [ref norse decom].

There are data presented for both lead-210 and polonium -210 as part of the Geotracers programme but none of these are in the North East Atlantic area. Data are available for the surface waters in the Atlantic (Po-210 ~ 1 mBq/l and Pb-210 3mBq/l) and Arctic (Po-210: 0.2- 0.4 mBq/l and Pb-210: 0.4-0.9 mBq/l) surface waters indicate that concentrations of Po-210 are approximately 0.4 mBq/l in the Arctic and of a few mBq/l or less in surface waters. A typical low-end background value of 0.4 mBq/l was therefore chosen for both radionuclides.

The OSPAR monitoring data base contains no lead-210 measurements and only 23 polonium-210 measurements.

Due to the limited number of Po-210 data available in the OSPAR database, the highest value reported was chosen as the typical high-end value. In the absence of any other data, the typical low and high-end values selected for Po-210 have been used for Pb-210, assuming secular equilibrium between these two radionuclides. The difference between low and high-end values (the range) is a measure of the variability of background levels for each naturally occurring radionuclide.

3.3 Reference activity concentrations in seawater

OSPAR Agreement 2016-07 (2022 Update) presents a methodology for deriving Environmental Assessment Criteria (EAC) for activity concentrations of radioactive substances in the marine environment of the OSPAR maritime area. The methodology is based on the methodology developed by the International Atomic Energy Agency (IAEA) to assess the radiological impact on humans and non-humans in an integrated manner (IAEA, 2015[4]). The EAC are in the form of reference activity concentrations in filtered seawater (Cref) which equate to whichever is the lower of the concentrations that would give rise to an annual radiation dose of 1 millisievert (mSv) to humans or a radiation dose rate at the lower bound of the relevant Derived Consideration Reference Level (DCRL), as defined by the International Commission on Radiological Protection for key marine Reference Animals and Plants.

The Cref values for the relevant OSPAR indicator radionuclides are given in Table 3. These values are intended for screening purposes and are therefore also applicable for assessing additional concentrations due to discharges.

Table 3. Environmental Assessment Criteria for relevant OSPAR Indicator Radionuclides

OSPAR Indicator Radionuclide	Cref values (Bq/l, filtered seawater)
Ra-226	2.60E-02
Ra-228	6.70E-02
Po-210	1.10E-04
Pb-210	8.80E-04

4 Far-field modelling and assessment approach

This section describes the far-field modelling and assessment approach, as developed specifically to support the Fifth Periodic Evaluation.

Additional concentrations across the OSPAR Maritime Area arising from discharges of produced water in different OSPAR regions were estimated using an established compartmental model. These data were evaluated against the objectives for radioactive substances of the NEAES 2010-2020, specifically to investigate whether activity concentrations of naturally occurring radioactive substances are "near background values". A screening radiological assessment was also undertaken by comparing the predicted additional concentrations with a fraction of the Environmental Assessment Criteria (EAC) [OSPAR Agreement 2016-07 (2022 Update), using an approach consistent with that used for artificial radionuclides.

4.1 Estimation of additional concentrations

4.1.1 Modelling system approach

The far-field modelling assessment was undertaken by the Public Health England (PHE) Centre for Radiation, Chemical and Environmental Hazards (CRCE)[8] using the PC CREAM 08 assessment software (Version 2.0), a code developed and maintained by PHE and predecessor organizations. The marine modelling module 'DORIS' [Ref 1] is a compartmental model consisting of a water dispersion model and a sedimentation model. There are 55 marine compartment areas (see Figure 3).

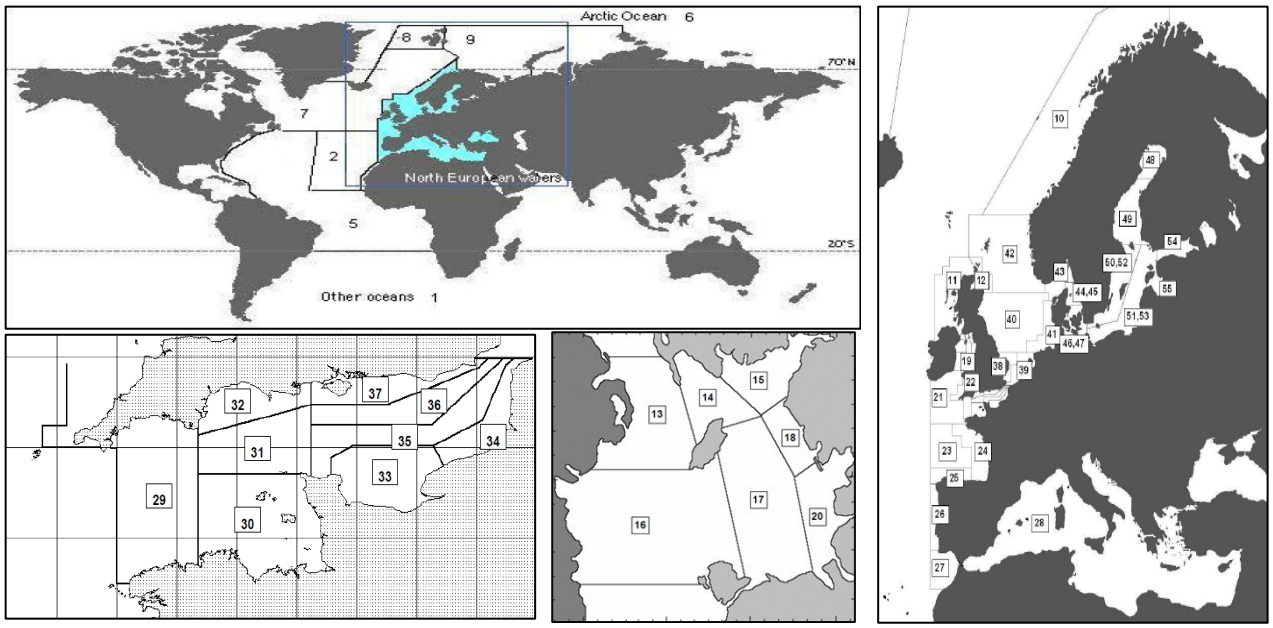

Figure 3: DORIS marine compartments (clockwise from top left): Ocean, European, Irish Sea and English Channel compartments

Compartmental analysis is used to model the movements of radioactivity between different parts of the marine environment, i.e., between water in one compartment and that in adjacent compartments and within a compartment between the water and the bed sediment. This includes in some areas use of up to three vertical water compartments with exchanges between them (e.g., Atlantic North NE, Kattegat, Belt

[8] Note, in March 2021, the UK Government announced the creation of a new UK Health Security Agency (UKHSA). All the radiation protection services currently provided by the CRCE within PHE will transfer into UKHSA. It is expected that the administrative process to complete the establishment of this new body will be completed in 2021.

Sea and Baltic Seas). Where this is the case, DORIS only includes interaction with sediments via the bottom water layer.

This modelling approach assumes instantaneous uniform mixing within each compartment, with transfer between interlinked compartments being proportional to the inventory of material in the source compartment.

In general, radionuclide transport in the water column is modelled by an advective flux representing the action of currents. However, it should be noted that for deep compartments, especially in the Atlantic Ocean region, turbulent diffusion is important, particularly in terms for vertical transport.

Adsorption of activity by sediments can result in significant depletion of activity from the water phase. Such depletion is due to both the partitioning of the activity between the liquid phase and the solid phase (suspended sediments and their subsequent deposition to the sea bed) and the removal of activity from the water column direct to bottom sediments. This adsorption is radionuclide-specific, controlled by the chemical properties of each radionuclide. DORIS also accounts for radioactive decay and ingrowth of decay progeny.

The DORIS compartments were primarily set-up to support the radiological assessment of radioactive releases from nuclear facilities in Europe and do not fully match those of the OSPAR Regions of (I) Artic Waters; (II) Greater North Sea; (III) Celtic Sea; (IV) Bay of Biscay and Iberian Coast; and (V) Wider Atlantic. The spatial relationship between the DORIS compartments, OSPAR Regions and OSPAR RSC Regions is shown in Figures 4 and 5, respectively.

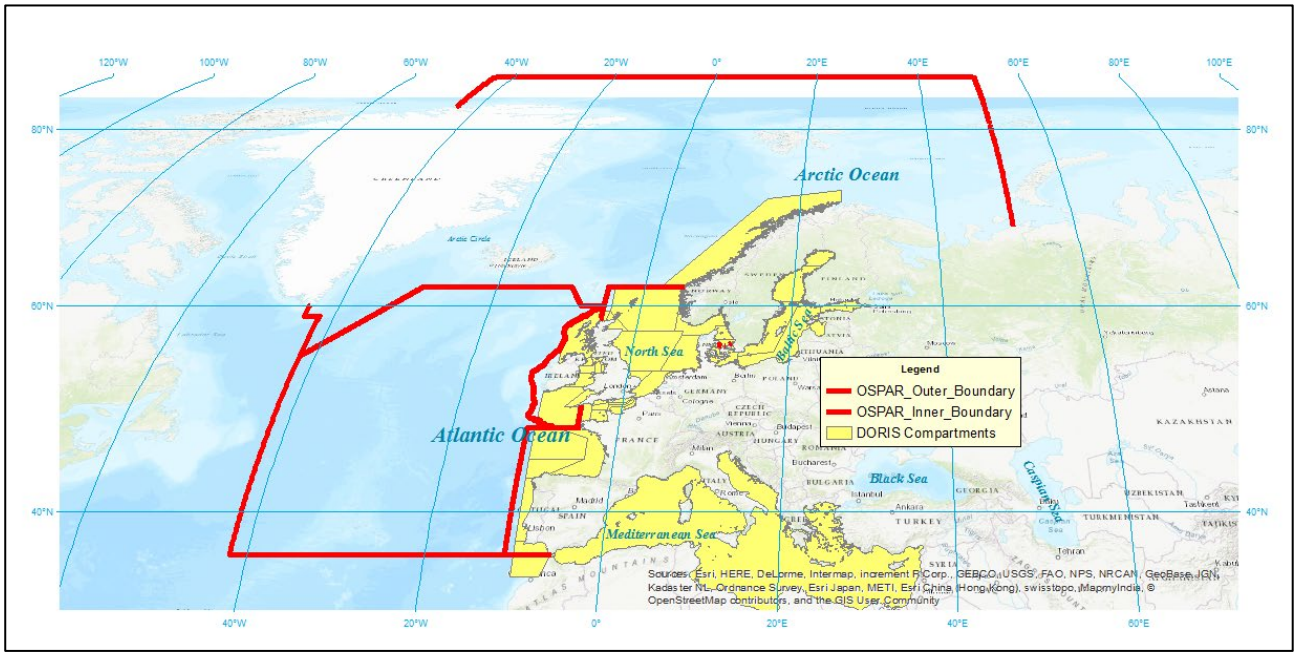

Figure 4: Spatial relationship between the DORIS compartments and the OSPAR Regions

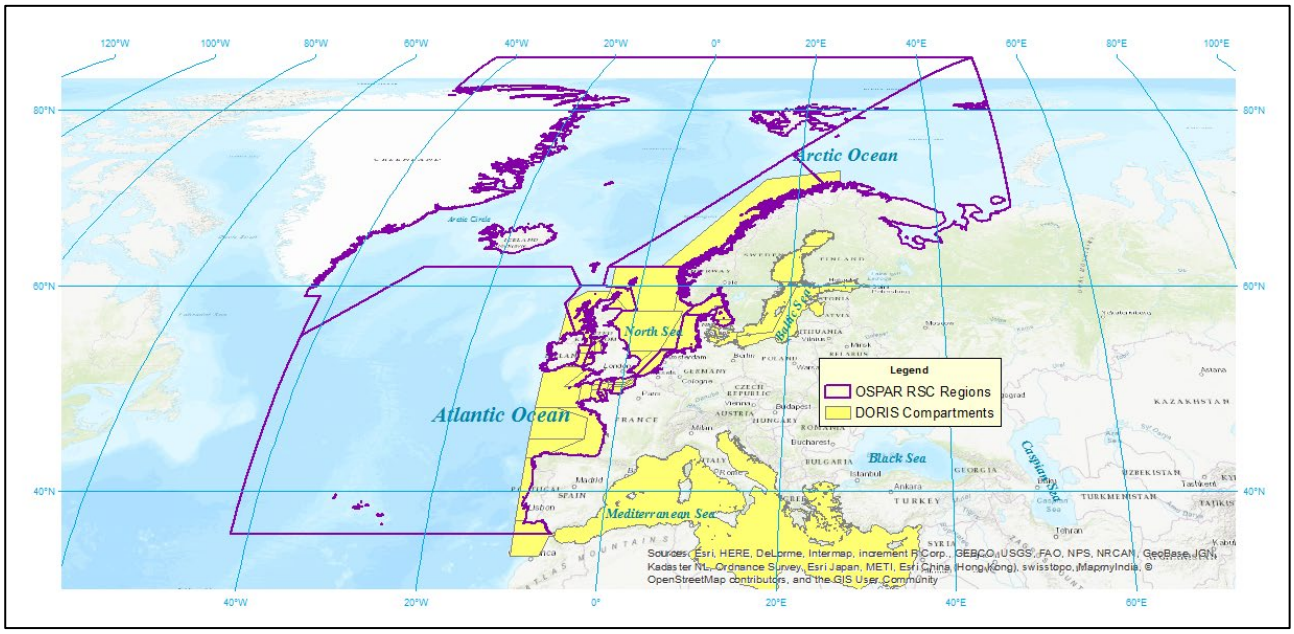

Figure 5: Spatial relationship between the DORIS compartments and the OSPAR RSC Regions

4.1.2 Method and input parameters and assumptions

The 180 discharging installations identified in the data collection exercise (see Section 3) were plotted using a GIS, using the location data in the OSPAR Offshore Installations Inventory 2015, and overlaid on the DORIS compartments. Nine DORIS compartments were identified as containing varying numbers of discharging installations, as shown in Figure 6.

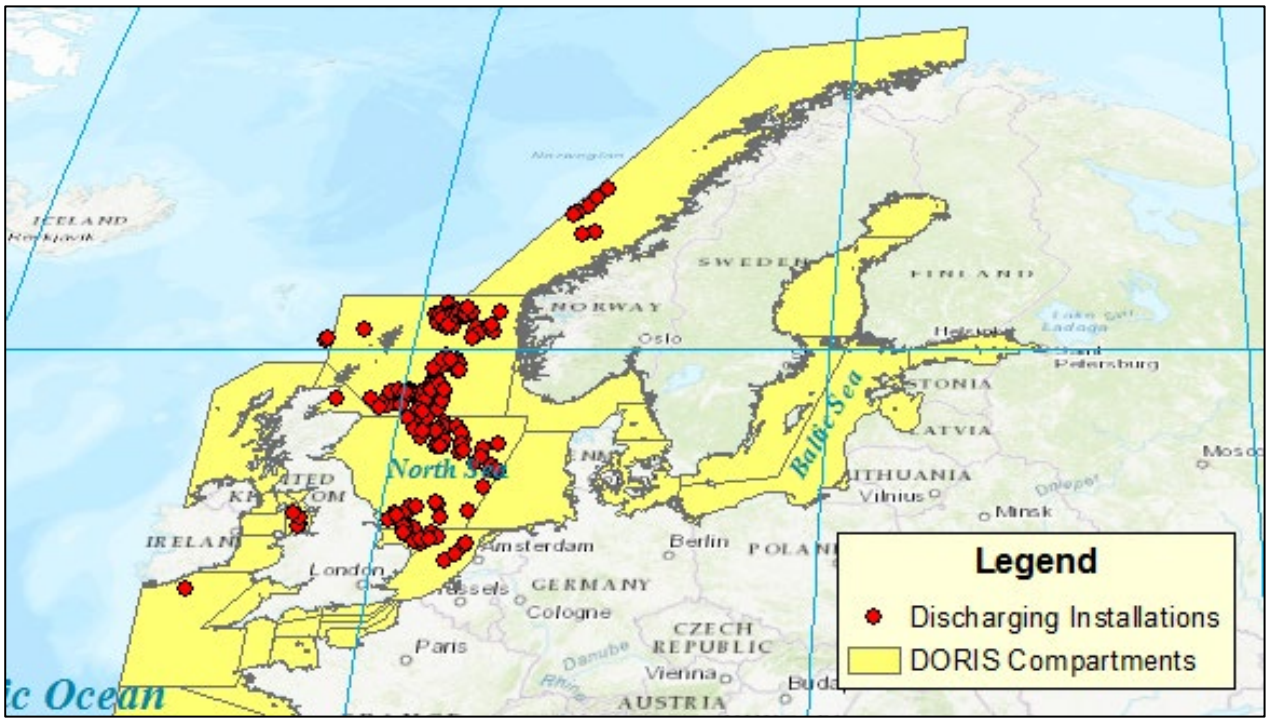

Figure 6 - Spatial distribution of discharging installations in relation to the DORIS marine compartments.

The nine compartments with discharging installations are referred to as *source compartments* and the remaining 46 compartments, which do not contain any discharging installations, are referred to as *recipient compartments*.

The regional source compartments in DORIS are:

- Atlantic Ocean North East
- Celtic Sea
- Irish Sea South
- North Sea Central
- North Sea North
- North Sea South East
- North Sea South West
- Norwegian Sea
- Scottish Waters

The total annual discharge into each source compartment, for the period 2006 – 2015, was estimated for the purposes of this assessment, as described in Section 3. These data are presented in Tables 4 - 6. Further details and installation-specific data are available in the OSPAR Data & Information Management System (ODIMS).

[1] Health Protection Agency (2015). The Methodology for Assessing the Radiological Consequences of Routine releases of Radionuclides to the Environment Used in PC-CREAM 08. Ref. HPA-RPD-058, Report Version 1.1, June 2015 (first published in November 2009)

Table 4 Annual total activity of Pb-210 discharged into DORIS 'Source' Compartments (MBq), 2006 – 2015

DORIS Regional Compartment	**Total activity of Pb-210 discharged (MBq)**									
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Atlantic Ocean North East	7.67E+03	7.97E+01	6.54E+02	6.54E+02	2.26E+02	1.17E+02	1.50E+02	1.06E+02	5.51E+00	4.10E+01
Celtic Sea	2.04E+00	2.18E+00	3.00E+00	1.77E+00	1.73E+00	1.31E+00	1.40E+00	1.26E+00	9.38E-01	1.08E+00
Irish Sea South	1.97E+04	3.13E+02	3.37E+02	3.37E+02	3.07E+02	3.69E+02	2.85E+02	6.71E+01	4.89E+01	6.06E+01
North Sea Central	1.01E+04	1.23E+04	2.08E+04	2.20E+04	7.50E+03	7.53E+03	8.65E+03	7.19E+03	9.27E+03	8.31E+03
North Sea North	7.81E+04	6.35E+04	1.23E+05	1.23E+05	5.82E+04	4.28E+04	4.17E+04	3.47E+04	2.11E+04	2.89E+04
North Sea South East	3.32E+03	4.54E+03	4.90E+03	1.63E+04	3.51E+03	3.33E+03	2.99E+03	2.78E+03	2.86E+03	2.67E+03
North Sea South West	2.58E+01	3.80E+01	2.59E+02	2.59E+02	1.01E+01	8.89E+00	8.35E+00	2.01E+01	1.08E+01	5.27E+00
Norwegian Sea	2.24E+03	5.71E+03	5.02E+03	7.29E+03	7.07E+03	4.39E+03	5.34E+03	4.08E+03	2.93E+03	2.64E+03
Scottish Waters	5.73E+02	4.49E+02	3.21E+03	3.21E+03	1.81E+03	1.96E+04	0.00E+00	2.00E+02	6.74E+01	8.95E+00

Table 5 Annual total activity of Ra-226 discharged into DORIS 'Source' Compartments (MBq), 2006 – 2015

DORIS Regional Compartment	**Total activity of Ra-226 discharged (MBq)**									
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Atlantic Ocean North East	5.02E+02	4.34E+02	3.19E+02	3.19E+02	4.86E+02	6.79E+01	4.31E+02	3.10E+02	4.56E+01	1.61E+02
Celtic Sea	2.36E+00	3.11E+00	4.39E+00	2.54E+00	2.48E+00	1.85E+00	2.04E+00	1.83E+00	1.16E+00	9.63E-01
Irish Sea South	2.55E+04	1.21E+04	5.97E+03	5.97E+03	5.44E+03	6.55E+03	1.03E+05	5.20E+03	4.31E+03	8.98E+03
North Sea Central	1.32E+05	1.42E+05	1.86E+05	2.04E+05	2.01E+05	2.41E+05	2.61E+05	1.48E+05	1.36E+05	1.43E+05
North Sea North	5.63E+05	5.79E+05	5.59E+05	5.55E+05	6.22E+05	5.08E+05	5.16E+05	4.82E+05	4.54E+05	5.18E+05
North Sea South East	8.65E+04	9.22E+04	1.19E+05	1.26E+05	1.03E+05	9.96E+04	8.85E+04	8.51E+04	9.34E+04	8.87E+04
North Sea South West	3.50E+02	5.19E+02	1.74E+02	1.74E+02	2.04E+02	7.19E+02	9.74E+01	2.74E+02	3.20E+02	4.42E+01
Norwegian Sea	3.89E+04	4.13E+04	4.55E+04	6.52E+04	5.88E+04	5.37E+04	5.70E+04	4.36E+04	4.79E+04	5.24E+04
Scottish Waters	2.99E+03	1.03E+03	1.13E+03	1.13E+03	8.37E+02	1.76E+03	0.00E+00	1.49E+03	9.54E+02	6.79E+01

Table 6 Annual total activity of Ra-228 discharged into DORIS 'Source' Compartments (MBq), 2006 – 2015

	Total activity of Ra-228 discharged (MBq)									
DORIS Regional Compartment	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Atlantic Ocean North East	4.52E+02	3.92E+02	7.42E+02	7.42E+02	6.02E+02	1.54E+02	6.11E+02	3.87E+02	7.63E+01	3.32E+02
Celtic Sea	6.01E-01	5.90E-01	8.98E-01	4.82E-01	4.38E-01	3.46E-01	3.56E-01	3.19E-01	1.84E-01	1.76E-01
Irish Sea South	3.12E+04	1.19E+04	3.87E+03	3.87E+03	3.53E+03	4.24E+03	4.47E+03	3.74E+03	3.02E+03	6.28E+03
North Sea Central	6.73E+04	6.50E+04	5.82E+04	5.91E+04	5.52E+04	8.50E+04	1.09E+05	5.85E+04	5.11E+04	7.01E+04
North Sea North	5.28E+05	4.86E+05	4.78E+05	4.67E+05	4.08E+05	4.39E+05	4.43E+05	4.26E+05	4.09E+05	4.54E+05
North Sea South East	1.38E+05	1.20E+05	1.27E+05	1.27E+05	1.25E+05	1.16E+05	1.10E+05	1.13E+05	1.21E+05	1.15E+05
North Sea South West	1.35E+02	4.43E+02	1.91E+02	1.91E+02	8.65E+01	7.87E+01	8.10E+01	1.79E+02	3.16E+02	4.11E+01
Norwegian Sea	3.62E+04	3.79E+04	4.16E+04	5.04E+04	4.53E+04	4.08E+04	4.57E+04	3.87E+04	4.29E+04	5.31E+04
Scottish Waters	3.39E+03	2.43E+03	1.81E+03	1.81E+03	1.27E+03	2.11E+04	0.00E+00	2.29E+03	1.96E+03	2.28E+02

DORIS was run for nine source terms (total annual discharges of NORM in produced water) in nine different regional compartments. To run DORIS, a 'local compartment' was defined into which the discharges occur and a rapid exchange of water and activity between the local and regional source compartments was assumed to ensure that there was no artificial delay in the dispersion of activity into the regional compartment. The local compartment parameters are the same as the PC-CREAM 08 defaults, but an exchange rate of 1 10E+15 m^3/y between local and regional compartment was used.

The total discharges for each radionuclide for each DORIS source compartment for each year (2006 – 2015) presented in Tables 1 – 3 were used to estimate activity concentrations in filtered seawater (i.e., the dissolved activity concentration) and bed sediment in each of the 55 compartments resulting from the cumulative discharges over the 10-year period.

In addition to the discharged Pb-210, Ra-226 and Ra-228, assumptions were made regarding secular equilibrium and radioactive progeny. It has been assumed that bismuth-210 (Bi-210) and polonium-210 (Po-210) were in secular equilibrium with the discharged Pb-210, and were therefore assumed to be discharged at the same level of activity and then modelled explicitly. DORIS also explicitly models radioactive progeny, which are not in secular equilibrium with their immediate parent within 1 year, while those which are in secular equilibrium are assumed to have the same activity as their immediate parent. These assumptions are summarised in Table 7.

Table 7 - DORIS modelling assumptions regarding secular equilibrium and radioactive progeny

Discharged radionuclides	**Progeny considered post discharge**
Bi-210(a)	Po-210(b)
Pb-210	Bi-210(c), Po-210(b)
Po-210(a)	-
Ra-226	Rn-222(c), Po-218(c), Pb-214(b), Bi-214(b), Po-214(c), Pb-210(b), Bi-210(c), Po-210(b)
Ra-228	Ac-228(c), Th-228(b), Ra-224(c), Rn-220(c), Po-216(c), Pb-212(b), Bi-212(b), Po-212(c)

(a) Assumed to be in secular equilibrium with discharged Pb-210 so discharged at the same level of activity
(b) Not in secular equilibrium so modelled explicitly
(c) Assumed to be in secular equilibrium with the immediate parent in the environment

4.1.3 Results

The DORIS model was used to estimate filtered seawater and bed sediment activity concentrations for all discharged radionuclides and radioactive progeny in all compartments. However, for the purposes of this report, only data for key indicator radionuclides (Po-210, Pb-210, Ra-226 and Ra-228) are presented. Filtered seawater results are provided below. The corresponding data for bed sediments are presented in Appendix A.

4.1.3.1 Activity concentrations in source and recipient compartments

The activity concentrations across all compartments span several orders of magnitude ranging from 10^{-15} to 10^{-5} Bq/l. An extract of the results showing the activity concentrations for the 9 source compartments is presented in Table 8 and in the remaining 46 recipient compartments in Table 9. The DORIS compartment numbers in these two tables are shown in Figure 3. These data are also illustrated in Figure 7, for the European compartments.

Table 8. Filtered seawater activity concentrations (Bq/l) in source compartments after 10 years of discharges (2006 – 2015)

Source Compartment		Po-210	Pb-210	Ra-226	Ra-228
2/3/4	Atlantic Ocean North East	5.19E-10	5.14E-10	3.54E-09	7.81E-10
10	Norwegian Sea	1.57E-08	1.94E-08	4.21E-06	1.96E-06
12	Scottish Waters East	8.17E-08	9.92E-08	8.20E-07	2.38E-07
14	North Sea North	4.06E-09	3.21E-09	8.62E-06	6.29E-06
19	Irish Sea South	3.18E-07	4.16E-07	6.20E-06	2.99E-06
21	Celtic Sea	1.46E-09	1.82E-09	2.56E-08	1.01E-08
38	North Sea South West	9.21E-07	1.23E-06	1.24E-05	8.27E-06
39	North Sea South East	6.03E-07	7.32E-07	1.58E-05	1.88E-05
40	North Sea Central	1.03E-06	1.30E-06	1.34E-05	6.67E-06

Table 9. Filtered seawater activity concentrations (Bq/l) in recipient compartments after 10 years of discharges (2006 – 2015)

Recipient Compartment		Po-210	Pb-210	Ra-226	Ra-228
1	Other oceans	1.02E-15	2.81E-15	6.47E-13	2.15E-13
5	Other Atlantic	4.10E-13	8.79E-13	2.04E-10	6.93E-11
6	Arctic Ocean	1.01E-10	1.18E-10	2.24E-08	7.88E-09
7	Arctic South	4.45E-11	1.14E-10	3.77E-08	1.45E-08
8	Spitzbergen	4.54E-11	8.51E-11	3.26E-08	1.21E-08
9	Kara and Barents Sea	6.64E-08	8.68E-08	1.23E-06	4.99E-07
11	Scottish Waters W.	5.67E-08	6.98E-08	5.70E-07	9.94E-08
13	Irish Sea N.W.	4.40E-07	5.68E-07	4.97E-06	1.33E-06
15	Irish Sea N.E.	4.08E-07	5.77E-07	4.65E-06	1.16E-06
16	Irish Sea W.	4.20E-07	5.55E-07	5.67E-06	1.98E-06
17	Irish Sea S.E.	4.23E-07	5.71E-07	5.30E-06	1.67E-06
18	Cumbrian Waters	3.42E-07	5.20E-07	4.35E-06	1.19E-06
20	Liverpool and Morecambe Bays	2.67E-07	4.49E-07	3.60E-06	9.60E-07
22	Bristol Channel	1.79E-09	2.31E-09	2.49E-08	7.84E-09
23	Bay of Biscay	2.41E-10	2.08E-10	1.01E-08	2.64E-09
24	French Continental Shelf	7.24E-11	5.87E-11	1.27E-08	3.83E-09
25	Cantabrian Sea	3.32E-11	2.58E-11	8.89E-09	2.30E-09
26	Portuguese Continental Shelf	2.81E-11	2.05E-11	3.54E-09	7.88E-10
27	Gulf of Cadiz	8.92E-11	6.81E-11	3.17E-09	6.82E-10
28	Mediterranean	1.16E-12	8.38E-13	1.45E-10	4.23E-11
29	English Channel W.	4.86E-09	6.31E-09	8.39E-08	7.19E-08
30	Channel Islands	1.32E-08	1.75E-08	2.41E-07	2.42E-07
31	Cap de la Hague	1.81E-08	2.36E-08	3.48E-07	3.64E-07
32	Lyme Bay	1.64E-08	2.18E-08	3.17E-07	3.30E-07
33	Baie de la Seine	6.54E-08	8.67E-08	1.37E-06	1.51E-06
34	Sam's Beach	7.60E-08	9.81E-08	1.70E-06	1.92E-06
35	Central Channel S.E.	6.46E-08	8.29E-08	1.41E-06	1.58E-06
36	Central Channel N.E.	6.94E-08	8.91E-08	1.52E-06	1.70E-06
37	Isle of Wight	6.84E-08	8.95E-08	1.52E-06	1.71E-06
41	North Sea E.	7.54E-07	9.99E-07	1.40E-05	1.31E-05

Recipient Compartment		Po-210	Pb-210	Ra-226	Ra-228
42	Irish Sea N.	4.33E-07	5.83E-07	5.05E-06	1.39E-06
43	Skagerrak	4.61E-09	3.96E-09	9.03E-06	6.84E-06
44	Kattegat (surface 0-20m)	1.01E-07	1.53E-07	5.43E-06	3.88E-06
45	Kattegat (bottom 20-120m)	1.08E-07	1.58E-07	8.60E-06	6.37E-06
46	Belt Sea (surface 0-14m)	7.06E-08	1.02E-07	2.86E-06	1.99E-06
47	Belt Sea (bottom 14-44m)	1.01E-07	1.54E-07	5.52E-06	3.95E-06
48	Bothnian Bay	4.12E-09	5.35E-09	2.97E-08	1.13E-08
49	Bothnian Sea	2.56E-08	3.15E-08	1.93E-07	7.91E-08
50	Baltic Sea E. (bottom 53-163m)	1.58E-07	1.98E-07	1.96E-06	1.04E-06
51	Baltic Sea E. (surface 0-53m)	1.22E-07	1.38E-07	1.01E-06	4.66E-07
52	Baltic Sea W. (bottom 49-159m)	1.49E-07	1.81E-07	1.40E-06	6.54E-07
53	Baltic Sea W. (surface 0-49m)	1.28E-07	1.43E-07	9.90E-07	4.37E-07
54	Gulf of Finland	5.47E-08	7.02E-08	4.63E-07	1.99E-07
55	Gulf of Riga	5.27E-08	7.14E-08	4.79E-07	2.08E-07

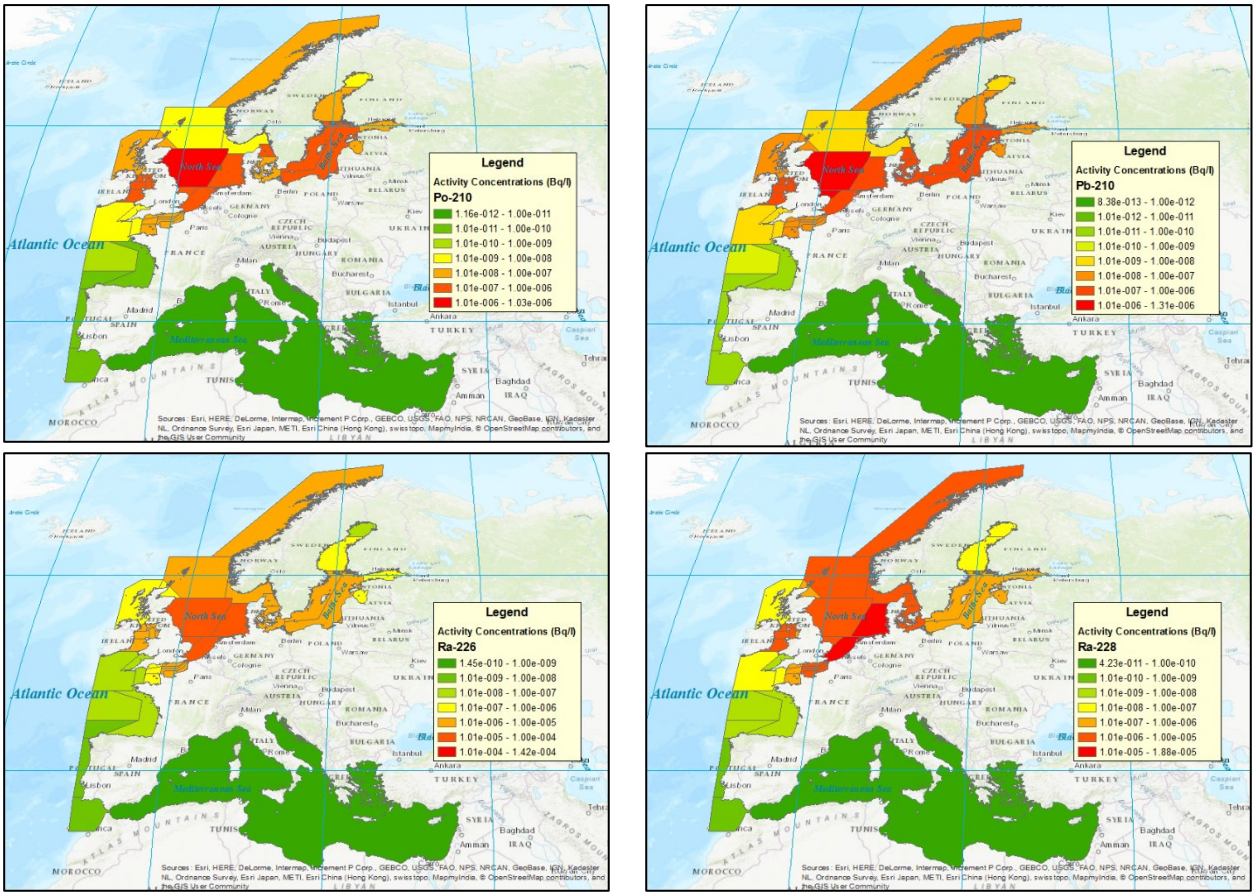

Figure 7: Filtered seawater activity concentrations (Bq/l) in European compartments after 10 years of discharges (2006 – 2015)

As might be expected, the radionuclide activity concentrations in seawater are higher close to the source of discharges than more distant from them. Furthermore, the concentrations in 'source' compartments tend to respond more quickly to changes in discharges that those in more distant recipient compartments.

The effect of distance from the discharges, on the estimated concentrations and relative contribution of different radionuclides, is illustrated in Figures 8 and 9 for one source compartment (North Sea Central) and one recipient compartment (Portuguese Continental Shelf).

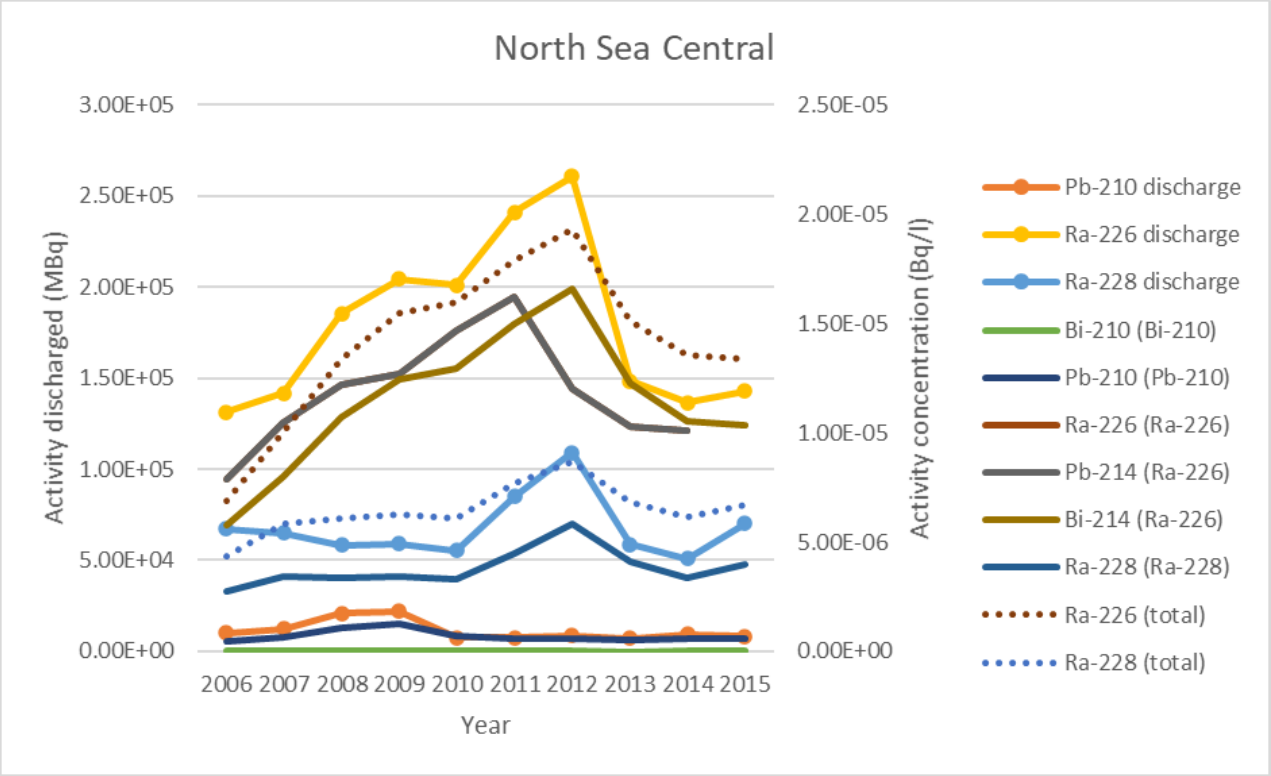

Figure 8: Discharges to the North Sea Central Regional Compartment and estimated activity concentrations in filtered seawater (Bq/l) in North Sea Central during 10 years of discharges to this compartment and from total discharges to all source compartments (total), (2006 – 2015).

Figure 8 demonstrates that the activity concentrations in filtered water closely follow the pattern of discharges into the source compartment. For example, there is a sharp decline in the activity concentrations of Ra-226 and Ra-228 in 2013 in response to the reductions in discharge of those radionuclides between 2012 and 2013. This figure also illustrates the total activity concentrations of these radionuclides (Ra-226 (total) and Ra-228 (total)), including the contribution from other source compartments. The difference in the level and slope of the plots for the Ra-226 (total) and (Ra-226 (Ra-226)) illustrates the enhancement in concentrations due to contributions from other compartments and also a lag in the response to changes in discharges in the local compartment, relative to the levels estimated from discharges into the local compartment alone.

Figure 9 illustrates the trends in the additional concentrations in the Portuguese Continental Shelf, a distant recipient compartment, as a result of discharges from all source compartments. The activity concentrations in this compartment demonstrate a gradually increasing trend, without the short-term fluctuations characterized by the source compartment. It is important to note that these values are orders of magnitude lower than those in the source compartments.

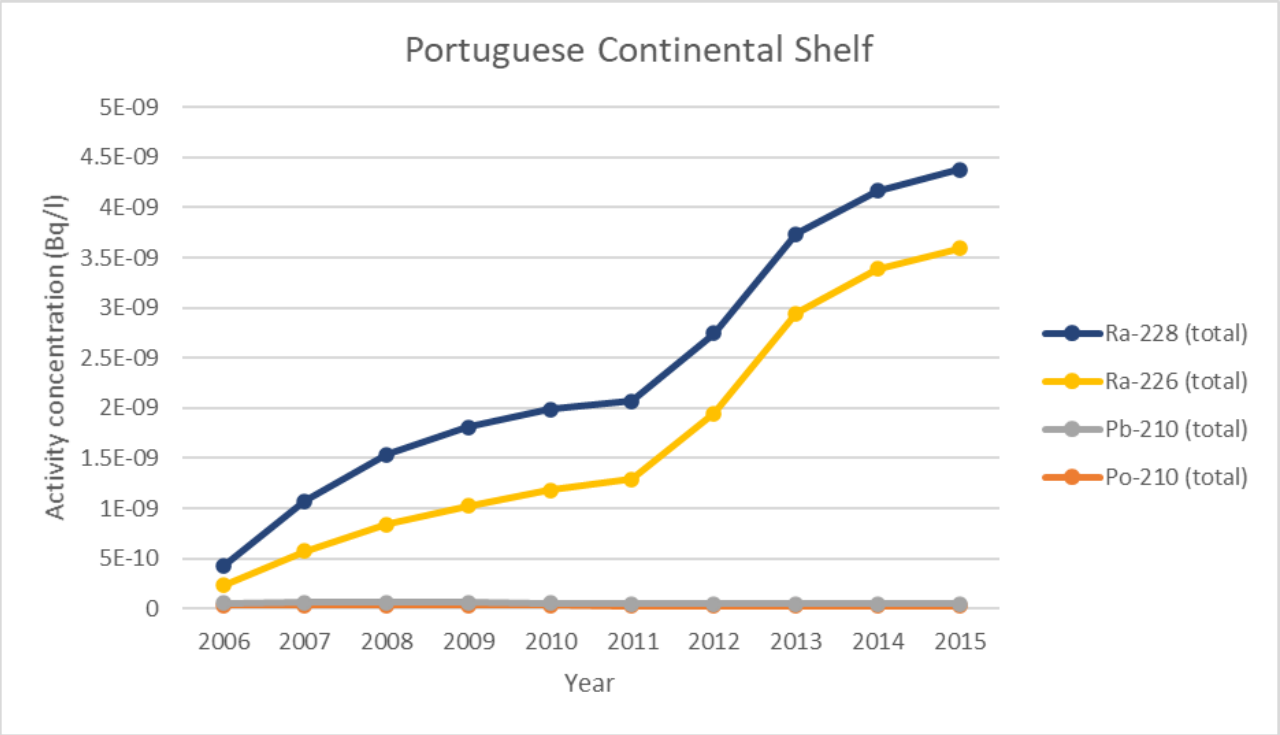

Figure 9: Filtered seawater activity concentrations (Bq/l) in Portuguese Continental Shelf during 10 years of discharges to all source compartments (2006 – 2015)

Recognizing that discharges have continued for longer than the assumed 10-year discharge period, additional work was undertaken to investigate the time taken for modelled seawater concentrations to reach a steady state, under continuous discharge conditions. The activity concentrations in the more distant compartments are, however, very much lower than those in source compartments.

4.1.3.2 Time to reach steady state and the contribution of progeny

Unit discharges of Pb-210, Ra-226 and Ra-228 were modelled in one source compartment for up to 10 million years, providing activity concentrations in filtered seawater in all 55 compartments over time. The progression towards a steady state for the source compartment, North Sea Central, and a distant recipient compartment, Portuguese Continental Shelf, is shown in Figures 10, and 11 respectively. The steady state activity concentrations and associated timescales are summarised in Table 10. A steady state is assumed to have been reached when the activity concentrations remain constant at two significant figures.

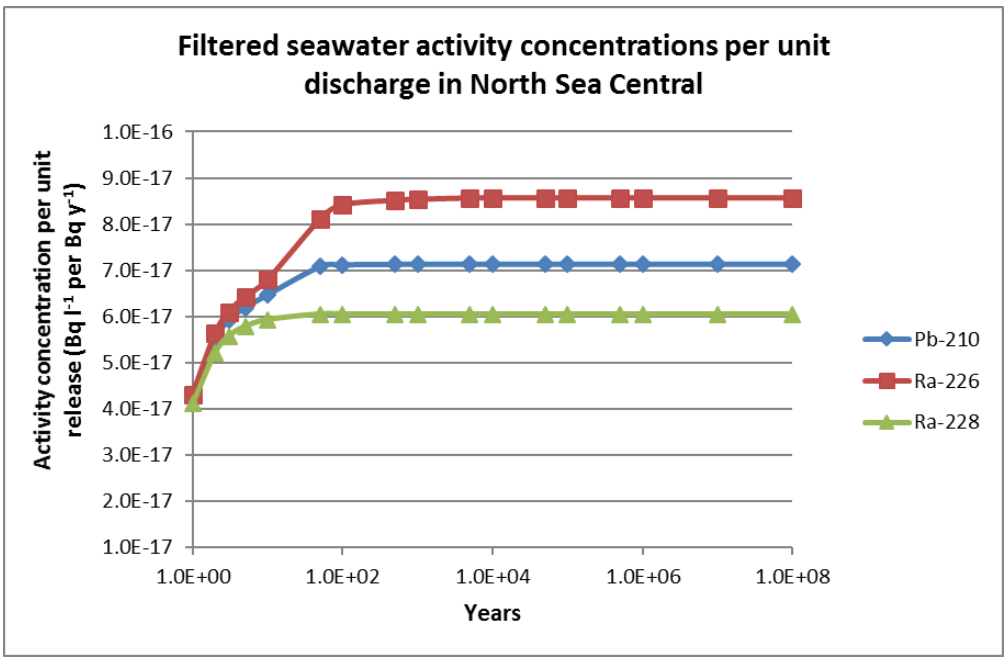

Figure 10: Filtered seawater activity concentrations (Bq/l) per unit discharge in North Sea Central

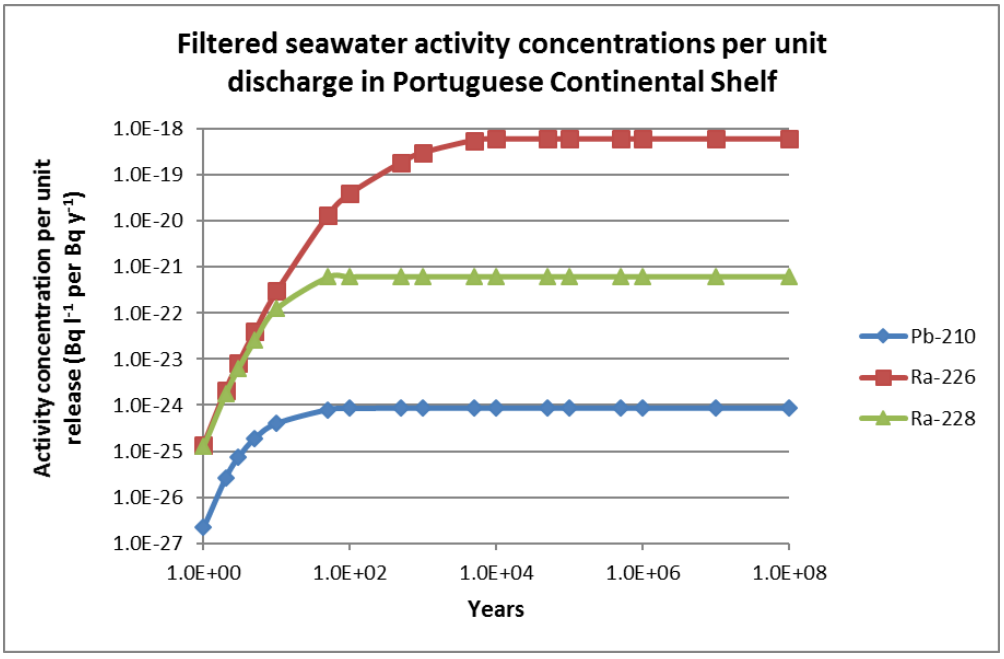

Figure 11: Filtered seawater activity concentrations (Bq/l) per unit discharge in Portuguese Continental Shelf

Table 10. - Comparison of per unit discharge activity concentrations (Bq/l) at a steady state and after 10 years

North Sea Central				
Radionuclide	Steady State (Bq/l)	Time to steady state (y)	10 y (Bq/l)	% of steady state
Pb-210	7.13E-17	100	6.47E-17	91
Ra-226	8.56E-17	5,000	6.79E-17	79
Ra-228	6.05E-17	50	5.93E-17	98
Portuguese Continental Shelf				
Radionuclide	Steady State (Bq/l)	Time to steady state (y)	10 y (Bq/l)	% of steady state
Pb-210	8.61E-25[9]	500	4.03E-25	47
Ra-226	6.03E-19	50,000	3.00E-22	0.05
Ra-228	6.22E-22	100	1.27E-22	20

Table 10 also includes the estimated concentrations after 10 years. A simple comparison of the estimated steady-state concentration indicates how close activity concentrations are to steady state, after 10 years of discharges. For North Sea Central, activity concentrations are close to a steady state after 10 years of discharges. Radium-226 is the radionuclide furthest from a predicted steady state reaching 79% of that value. As shown in Figure 10, seawater concentrations in the source compartment respond quickly to changes in discharges in that compartment. Discharges of Ra-226 in North Sea Central compartment in the 10-year modelling period varied by more than 20% (mean 0.18 TBq, min 0.13 TBq max 0.26 TBq) and therefore 79% is considered close enough to the predicted steady state concentration to be acceptable.

In contrast, for Portuguese Continental Shelf, the activity concentrations take longer to reach a steady state value due to the distance from the source compartment. However, the steady state the activity concentrations are orders of magnitude lower than those of the source compartments.

It is also interesting to note that activity concentrations closest to the discharges are dominated by the discharged radionuclides (Figure 12), whereas some radioactive progeny become relatively more important with increasing time and distance from the discharges, depending on their behaviour in the environment and their radioactive half-life (Figure 13).

[9] This value is from Pb-210 in discharges only and does not include the contribution from ingrowth from Ra-226 (which contributes to the higher concentrations, as illustrated in Fig. 13).

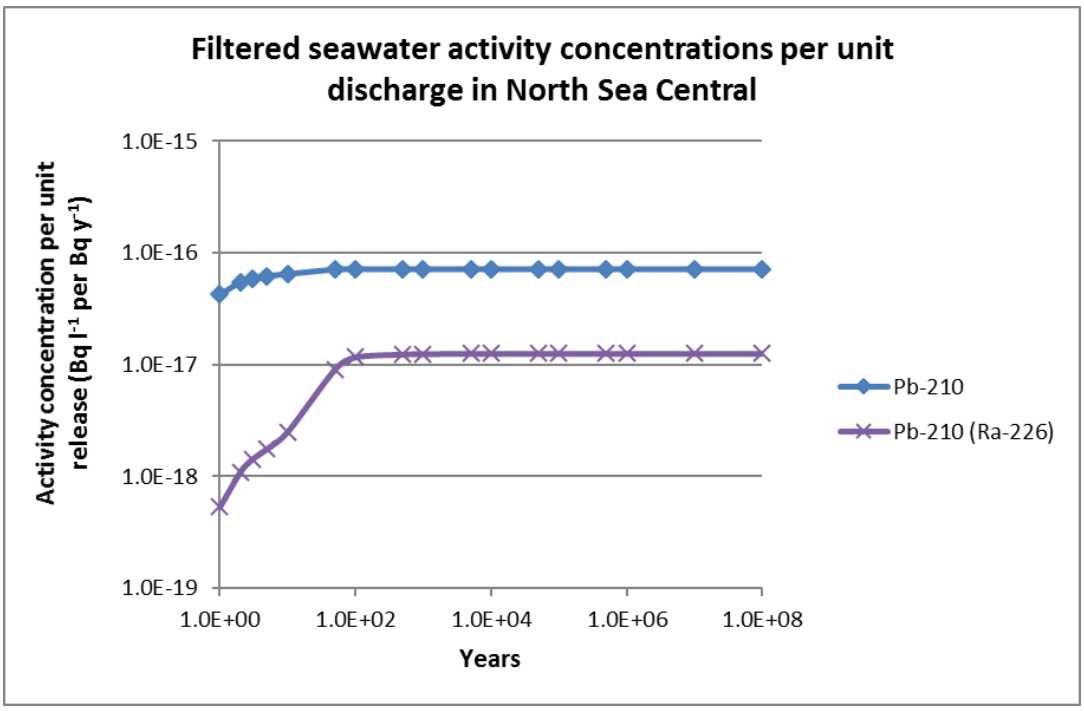

Figure 12 - Comparison of filtered seawater activity concentrations (Bq/l) per unit discharge for Pb-210 and the ingrowth of Pb-210 from Ra-226 in North Sea Central

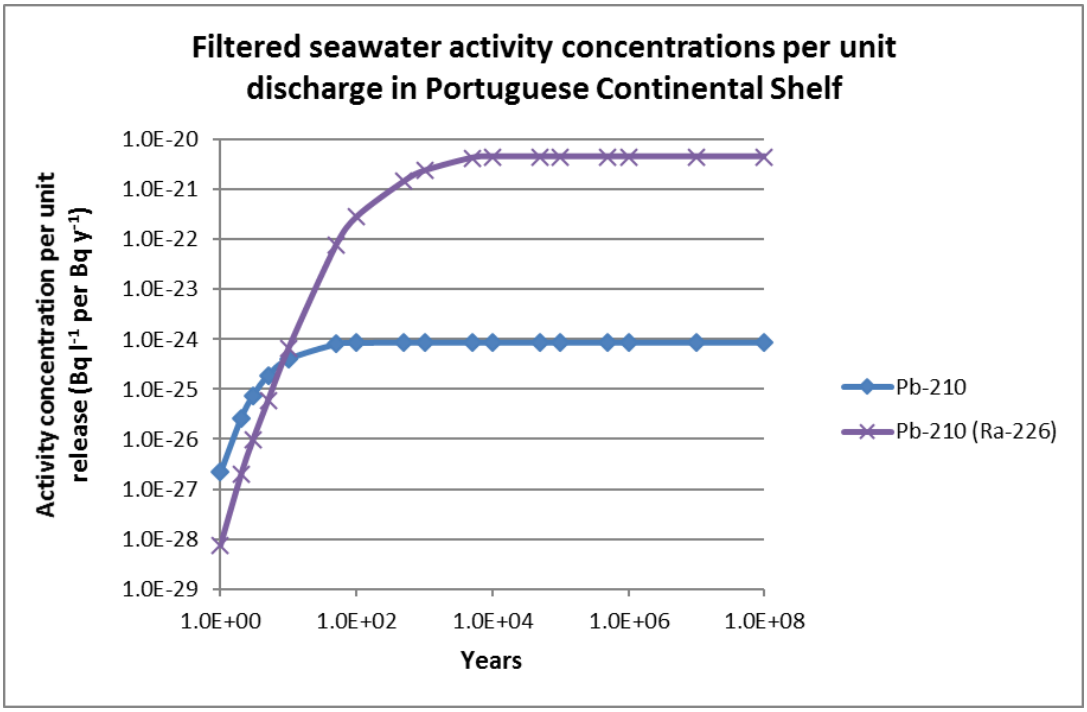

Figure 13 - Comparison of filtered seawater activity concentrations (Bq/l) per unit discharge for Pb-210 and the ingrowth of Pb-210 from Ra-226 in Portuguese Continental Shelf

4.2 Assessment of model predictions against OSPAR strategy objectives

As explained in the introduction to this report, the OPSAR RSS contains two objectives which are relevant to NORM. The first, the ultimate aim, is that concentrations in the environment are near background values for naturally occurring radioactive substances. The second, is that by 2020, additional concentrations [of radionuclides] in the marine environment above historic levels are close to zero. Unfortunately, there is insufficient data to evaluate historic levels so, unlike for artificial radionuclides, it is not possible to directly

assess progress against the second objective. Therefore, this assessment is focussed on the first objective of concentrations in the environment being near background values.

In order to assess whether concentrations are 'near background values', it is necessary to establish the background concentrations of the different natural radionuclides and also to establish what should be interpreted as 'near', as described in more detail in Section 3. The RSC decided that if the environmental concentrations, including the additional contribution from discharges of produced water, fall within the natural variability of the natural radionuclide in question it could be considered near background.

In order to assess whether total environmental concentrations of naturally occurring radionuclides are near background, the highest modelled additional concentrations of these radionuclides resulting from discharges of produced water from the non-nuclear oil and gas sub-sector were compared to the typical low-end estimate of background and with the variability (the range between low and high-end values) of the selected typical background levels. Due to the limited amount of monitoring data available for individual OSPAR RSC sub-regions this comparison was made for the whole OSPAR maritime area. Table 11 shows that, for all indicator radionuclides for naturally occurring radionuclides in produced water, the additional concentrations resulting from discharges of produced water from the oil and gas sub-sector were less than 1% of the indicative range in background levels.

The highest modelled additional concentrations were also compared with the typical low-end background values to provide a 'reasonable worst case' estimate of the maximum relative increase in total environmental concentrations. This comparison indicates that naturally occurring radionuclides discharged in produced water from the oil and gas sub-sector would result in additional concentrations of no more than 10% above representative low-end background values. To put this into context, it is worth noting that monitoring data reported to OSPAR for naturally occurring radionuclides in seawater often have measurement uncertainties that exceed 10%, as demonstrated in Tables 8 and 9. This means that in practice such additional concentrations would likely be indistinguishable from background levels measured by routine analytical measurement techniques, for environmental monitoring purposes.

Table 11. Comparison of modelled additional concentrations of indicator radionuclides for naturally occurring radionuclides in discharges of produced water to typical background levels of naturally occurring radionuclides in the OSPAR maritime area[1].

Indicator radionuclide	Typical range of background levels low – high (range)	Highest modelled additional concentration	Additional concentration as % of range	Additional concentration as % of low-end background value
Po-210	0.4 – 3.4 (3.0)	0.001	0.03%	0.25%
Pb-210	0.4 – 3.4 (3.0)	0.001	0.03%	0.25%
Ra-226	1.3 – 6.3 (5.0)	0.016	0.3%	1.2%
Ra-228	0.2 – 3.3 (2.8)	0.019	0.7%	9.5%

1 - Selection of the typical background values is described in brief in Chapter 3. The variability (range) is the difference between the typical low and high-end values. All values are presented in mBq/l

Thus, the modelled additional concentrations are therefore far less than indicative variations in background levels and a small fraction of typical low-end background levels. In addition, even in a reasonable worst case, the additional concentrations arising from discharges of produced water are within the range of measurement uncertainties such that they would not be measurable. These results indicate

that total environmental concentrations of natural radionuclides may be considered to be near background values.

4.3 Radiological Assessment

The radiological impact associated with the estimated additional concentrations was evaluated using reference activity concentrations in seawater (or Cref) values that represent the lower of either (i) concentrations that would give an annual effective dose of 1 mSv to people or (ii) the lowest Derived Consideration Reference Level (DCRL) to biota, below which biota are considered to be protected at a population level [Ref].For each radionuclide, the highest estimated additional concentrations (from all of the source compartments) was compared to 100th of the equivalent Cref value, which would equate to 10 µSv annual effective dose, which is widely accepted to represent a trivial risk. These data are provided in Table 12. All values are less than Cref/100, indicating the risk from each individual radionuclide is trivial.

Table 12. - Comparison of highest estimated addition activity concentration (at 10 years) with the selected background values

Nuclide	DORIS compartment	Estimated additional concentration (Bq/l)	Fraction ofCref/100
Ra-226	N. Sea SE	1.6E-05	0.06
Ra-228	N. Sea SE	1.9E-05	0.03
Po-210	N. Sea Central	1.3E-06	0.94
Pb-210	N. Sea Central	1.3E-06	0.15

4.4 Conclusions

In summary, the main conclusions that can be drawn from this work are as follows:

The modelled additional activity concentrations of Po-210, Pb-210, Ra-226 and Ra-228 in filtered seawater span several orders of magnitude, ranging from 10^{-15} to 10^{-5} Bq/l, with the highest concentrations in the source compartments and close to the discharges, with values in recipient compartments and at greater distance at the lower end of this range.

The modelled additional activity concentrations of radionuclides in filtered sea water in source compartments following 10 years' discharge were compared with the typical range of background values to determine whether total environmental concentrations of these naturally occurring radionuclides were near background values. For the indicator radionuclides, Po-210, Pb-210, Ra-226 and Ra-228, the additional concentrations of these radionuclides resulting from oil and gas discharges are less than 1% of the typical range in background levels.

The highest modelled additional concentrations were also compared with the typical low-end background values to provide a 'reasonable worst case' estimate of the maximum relative increase in total environmental concentrations. This comparison indicates that naturally occurring radionuclides discharged in produced water from the oil and gas sub-sector would result in additional concentrations of no more than 10% above low-end background values. This means that, in practice, any additional concentrations would likely be indistinguishable from background levels measured by routine analytical measurement techniques for environmental monitoring purposes.

Furthermore, additional concentrations of the NORM indicator radionuclides in seawater are lower than the fraction of the reference activity concentrations (Cref/100) that corresponds to a trivial annual dose of 10 µSv and also a small fraction of the doses rates which may give rise to effects in biota. Therefore, it is reasonable to conclude that these additional concentrations would not result in any radiological impact to humans or the marine environment.

These comparisons, taken together with assessment on radiological impact indicate that it is reasonable to consider, for seawater, that the ultimate aim of 'total environmental concentrations of naturally radionuclides are near background levels' is likely to have been achieved.

5 Near-field modelling approach

This section discusses the near-field modelling approach.

5.1 Modelling of data

5.1.1 Overview of assessment

In the immediate vicinity of individual installations, there are localised and transient fluctuations of activity concentrations. These conditions are not representative of the situation in OSPAR Regions or the wider Maritime Area. The results of near-field modelling are therefore not directly relevant to the Fifth Periodic Evaluation. However, it was recognised that information on the local situation may also be of interest. In the interests of transparency, a near-field modelling approach was applied to provide an estimate of the short-term fluctuations around installations. The near-field modelling approach is described in more detail in Ref [**Error! Bookmark not defined.**] and Ref [**Error! Bookmark not defined.**], appended as annexes to th is report.

Near-field modelling is a time consuming and complex modelling process and was therefore undertaken for a representative selection of installation selected from the UK and Norwegian waters to develop screening tool approach to apply to others (dilution factor look up table). Seven installations in the Norwegian sector and 16 installations in the UK sector were chosen. The key factors influencing selection of installations were the quantity of produced water discharged and the depth of water that the installation is situated in, as these have previously been observed to influence dilution of discharges. Installations were selected to represent the range of scenarios found in the OSPAR area. Additionally, installations were also selected to include those that give rise to the largest the quantity of radionuclides discharged, considering that these are likely to have the largest contribution to additional concentrations.

Installations were considered separately and it was assumed that there was no significant influence of neighbouring installations on the activity concentrations in the immediate vicinity of a given installation. Installations are generally separated from one another by more than a few kilometres, such that it is unlikely that there would be significant cumulative effects in the near field. Nevertheless, the distance between different installations was determined, in order to be able to investigate this in more detail, if necessary. This information is included in Appendix A of Annex B, for ease of reference.

Dilution factors were estimated at a distance of 500 m from the discharge points. This is a distance routinely used for regulatory purposes in determining non-radiological environmental risks, for a wide range of installation types, locations and discharge parameters. The approach adopted was deliberately conservative; for example related to the dispersion conditions, no sedimentation, and the application of concentrations along the centre of the discharge plume.

The correlation between (i) produced water discharge volume and dilution and (ii) installation water depth and dilution has also been investigated.

5.1.2 Modelling system approach

The numerical model DREAM (Dose related Risk and Effect Assessment Model), developed by SINTEF[10], is a dynamic three-dimensional particle dispersion module, capable of modelling the spatial transport of the individual components in the discharge plume over time. It can be used to assess initial dilution factors based on discharge characteristics and the nature of the receiving environment (e.g., wind and currents and turbulence in the sea). It also considers the descent / rise of a plume based on the density of the plume relative to that of the ambient environment. It is a tool routinely used for regulatory assessments associated with chemical water quality management in the oil and gas sector.

[10] 'Stiftelsen for industriell og teknisk forskning' (Foundation for Scientific and Industrial Research)

5.1.3 Method and input parameters and assumptions

For the purposes of this application, it was assumed that the radionuclides are in a dissolved state in the discharged water. A release depth of 20 m and a release duration of 30 days for the month of May were assumed, which was chosen as the month during which the currents are weakest and thus result in the least dilution of produced water. The assessment of the dilution was modelled on the basis of a tracer with the same density (i.e., considered to have the same temperature and salinity) as the ambient water and a concentration of 1,000 ppm in the produced water. The dilution factor at 500 m has then been calculated from the initial concentration.

The results in this study have been calculated from the 30-day time-series of concentration field that was modelled for each installation. The lowest dilution values in each grid cell during this period were identified and compiled to provide a map of minimum values (see Figure 13), and within that the lower, median and upper values at 500 m.

The model used a 5 x 5 x 5 m modelling grid with model output given every 30 minutes and modelled tidal current data for May 1990 for the Norwegian installations and 100 minutes output and a grid size of 10 x 10 m east-west to north-south and 5 m cell height for the UK installations.

Additional input information for two Norwegian installations have been modelled with the nearfield Plume3D model (also applied for the UK installations). This includes the effect of discharge pipe diameter on turbulence at the point of discharge and hence initial mixing and also the effect of pipeline discharge direction and temperature and salinity of the buoyancy of the plume (and hence initial dilution).

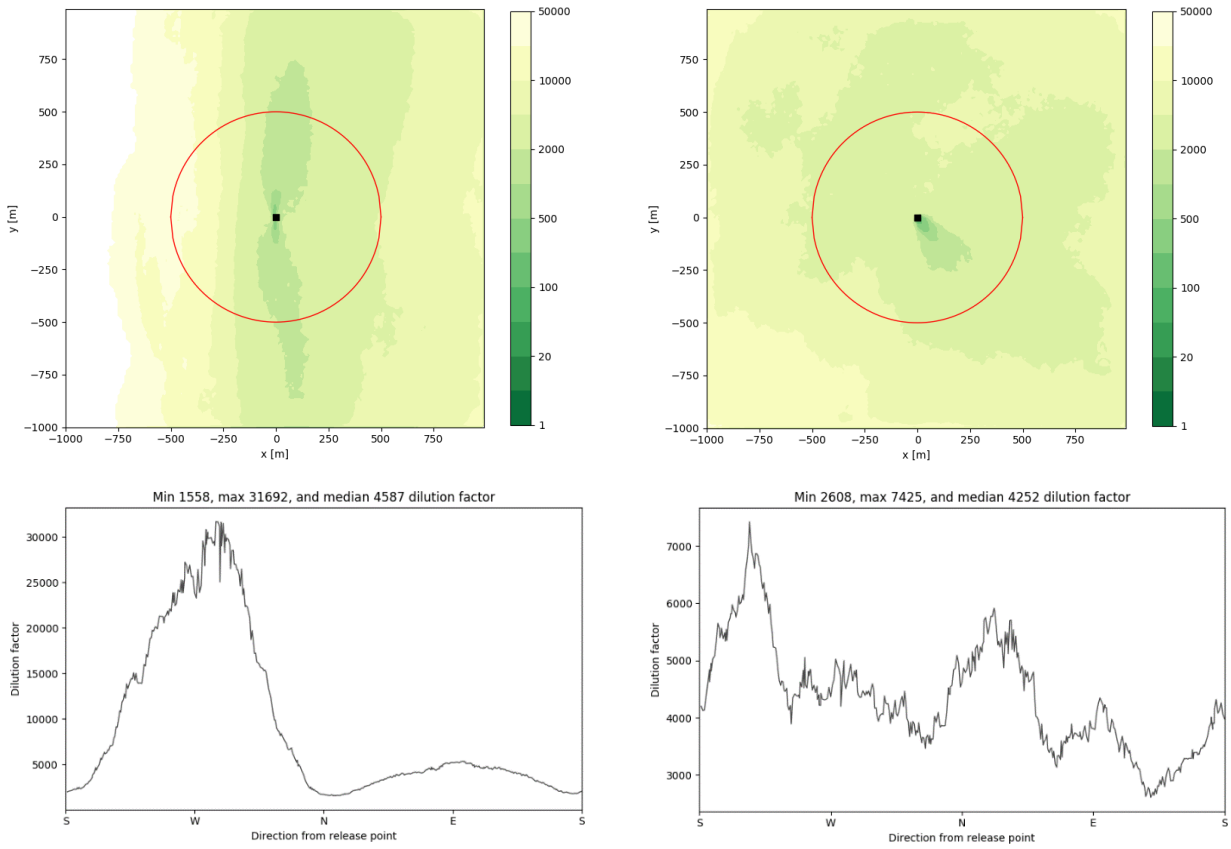

Figure 13 - Example of a map showing the all-time minimum dilution factor values at every grid cell for the 30-day modelling period.

5.1.4 Results

Near-field dilution results calculated over the 30-day modelling period at a 500 m distance (all directions) from the discharge point are discussed in Ref [**Error! Bookmark not defined.**] and Ref [**Error! Bookmark not de fined.**].

Momentary minimum dilutions between 47 and 16,239 at the most concentrated location in the plume were modelled, depending mainly on the discharge rate, along with average dilutions between 191 and 30,679 in the most concentrated location in the plume. It is considered that the minimum dilution results would be inappropriate in the context of actual exposure scenarios, or for drawing conclusions on potential impacts on a wider scale. The average dilution results (which only occur at the plume centreline, i.e., they are not the average concentration throughout the water column) are still likely to be upper estimates and were considered to be a more meaningful basis for consideration. By comparing the specific activity of discharges with the average dilutions, the concentrations of the three radionuclides (Pb-210, Ra-226 and Ra-228) can be estimated.

The dilution of the produced water discharge modelled without the near-field function in DREAM activated showed that the minimum values of the average dilution ranged between 173 and 23,338. For the Norwegian installations, the minimum values for the minimum dilution ranged between 47 and 8,561. The lowest dilution values are found at Troll B and Statfjord C (high discharge rate), while Oseberg S (low discharge rate) has the highest dilution values. Results from the near-field Plume3D model are more variable showing both increased and reduced dilution depending upon local conditions.

Modelled dilutions and specific activity are shown in Table 13.

Table 13. - Summary of dilution and activity concentration results from the near-field modelling

		Modelled maximum specific activity (Bq/l) in seawater at 500 m		
Code	**Dilution**	**Pb-210**	**Ra-226**	**Ra-228**
UK-A	19,012	1.33E-05	1.02E-04	5.90E-05
UK-B	11,565	5.82E-06	3.60E-04	2.69E-04
UK-C	20,045	4.54E-06	3.48E-04	1.39E-04
UK-D	4,136	1.36E-05	1.13E-03	8.59E-04
UK-E	7,622	4.85E-06	3.68E-05	1.24E-04
UK-F	5,053	8.83E-06	9.59E-04	4.05E-04
UK-G	2,535	9.10E-06	2.19E-03	1.54E-03
UK-H	30,679	8.46E-05	3.46E-04	2.27E-04
UK-I	3,659	1.35E-09	1.03E-04	2.16E-04
UK-J	11,425	2.08E-06	2.83E-05	3.50E-05
UK-K	13,310	3.98E-09	8.10E-09	2.93E-08
UK-N	2,608	4.14E-05	2.84E-05	8.41E-05
UK-O	12,753	4.38E-06	1.08E-04	8.91E-05
UK-P	1,316	4.09E-05	8.21E-04	5.52E-04
UK-Q	4,195	6.03E-06	1.62E-03	8.25E-04
UK-R	2,545	1.25E-05	1.68E-03	1.08E-03
Norway-1a	2,491	5.38E-07	1.45E-05	6.62E-06
Norway-2a	776	4.29E-06	3.75E-04	3.36E-04
Norway-1	1,023	1.31E-06	3.54E-05	1.61E-05
Norway-2	3,302	2.70E-07	2.30E-06	8.93E-07
Norway-3	23,338	5.01E-10	2.50E-08	2.13E-08
Norway-4	191	9.53E-06	5.86E-05	7.07E-05

		Modelled maximum specific activity (Bq/l) in seawater at 500 m		
Norway-5	173	1.92E-05	1.68E-03	1.51E-03
Norway-6	484	1.64E-06	1.20E-04	1.23E-04
Norway-7	4,131	3.70E-08	1.70E-06	1.06E-06

Median dilutions at 500 m as a function produced water discharged are plotted in Figure 14. There is a correlation between dilution and volume and produced water discharges but not with depth.

This shows that there is useable relationship between annual discharge of water and dilution at 500 m. This relationship can be expressed as:

Dilution factor = 10^(8.3301-0.8696*LOQ(Qpw)

Where Qpw is the annual discharge of produced water (m^3).

This relationship was used to derive the dilutions factors at 500 m, as shown in Table 14.
Table 14. Dilution Factor at 500 m as a function of annual discharge

Annual discharge of PW (m^3)	**1.00E+04**	**1.00E+05**	**1.00E+06**	**1.00E+07**	**1.00E+08**
Dilution at 500 m	71,072	9,596	1,296	175	24

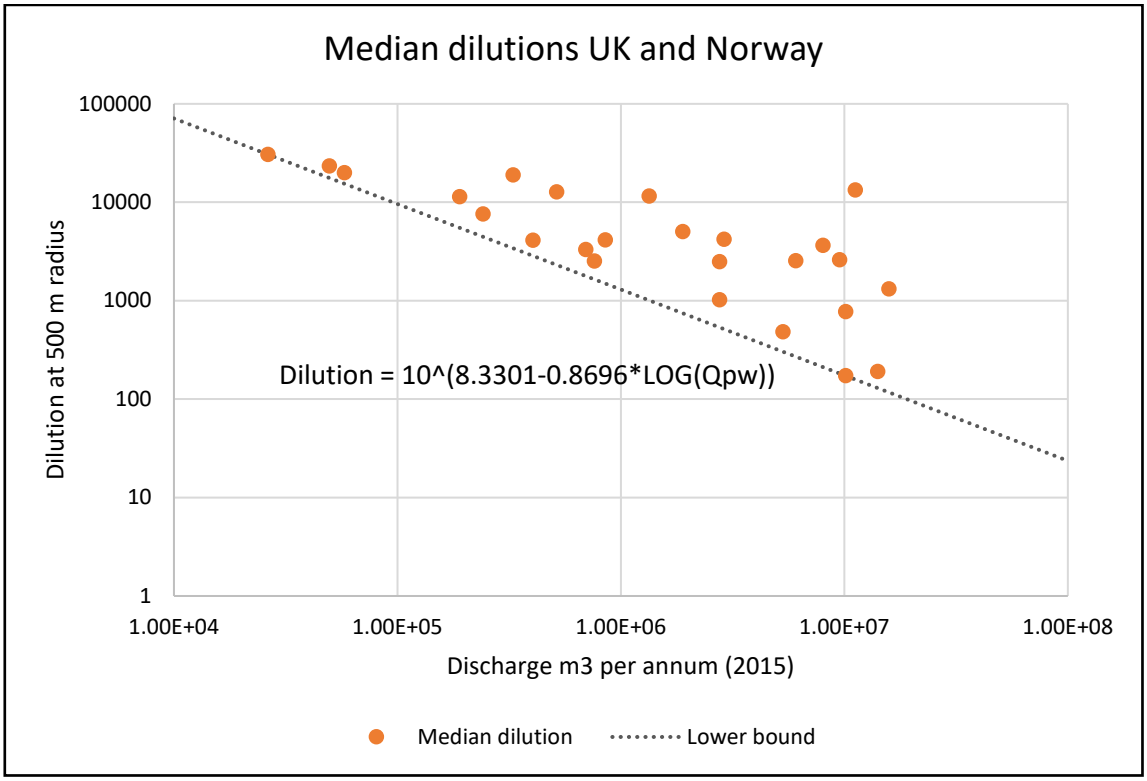

Figure 14 - Correlation plot of estimated dilution at 500 m vs quantity of produced water discharged.

The correlation between produced water discharges and dilution is a proportionate and suitable mechanism by which to calculate the dilution and radionuclide concentrations of those installations that were not explicitly modelled. This equation has been applied to all 180 installations considered in this work and results are presented in Appendix B.

5.2 Radiological Assessment

The estimated activity concentration data for the installations included in the near-field assessment (see Table 11) were compared to the environmental assessment criteria (or Cref values) and results (to two significant figures) are shown in Table 15. It was considered appropriate to compare these data with the Cref, rather than Cref/100, used in the assessment of far-field assessment results, given that the estimated concentrations from near-field modelling are upper bound estimates of the concentration at a given point in the water column, along the line of the release. They are therefore conservative estimates of localised and transient conditions, and a higher criterion is appropriate.

None of the UK installations considered in this assessment were estimated to result in a specific activity at 500 m of more than 10% of the Cref value, and most are below 5% of the Cref. Approximately 50% of the Norwegian installations considered result in estimated concentrations at 500 m below 10% of the Cref value, with one instance of the Cref being exceeded at 500 m. It should be noted that the modelling approaches used for UK and Norwegian installations are however slightly different, hence direct comparisons are difficult, although the modelling approach used for the Norwegian installations are likely to lead to higher results[11]. It should also be noted that the application of the dilution factor to other installations (see Appendix B) resulted in some cases where concentrations at 500 m were predicted to exceed this criterion.

Table 15. Summary of EAC comparison from the near-field modelling

	Modelled specific activity as proportion of Cref		
Code	**Pb-210**	**Ra-226**	**Ra-228**
UK-A	0.02	0.00	0.00
UK-B	0.01	0.01	0.00
UK-C	0.01	0.01	0.00
UK-D	0.02	0.04	0.01
UK-E	0.01	0.00	0.00
UK-F	0.01	0.04	0.01
UK-G	0.01	0.08	0.02
UK-H	0.10	0.01	0.00
UK-I	0.00	0.00	0.00
UK-J	0.00	0.00	0.00
UK-K	0.00	0.00	0.00
UK-N	0.05	0.00	0.00
UK-O	0.00	0.00	0.00
UK-P	0.05	0.03	0.01
UK-Q	0.01	0.06	0.01
UK-R	0.01	0.06	0.02
Norway-1a	0.00	0.00	0.00
Norway-2a	0.00	0.01	0.01
Norway-1	0.00	0.00	0.00

[11] The modelling for the UK sector used a 10 m grid size, while 5 m was used for the Norwegian sector. For UK installations, the near-field plume algorithm that takes into account near-field turbulent dispersion was applied. The use of the sub-model increases the dilution of the produced water locally and allows it to rise and sink in the water column, which affects its dispersion at 500 m, particularly where the plume encounters the surface or the seabed. The results quoted from Norway do not include this near-field dilution and so are likely to be more conservative than results from the UK.

	Modelled specific activity as proportion of Cref		
Code	**Pb-210**	**Ra-226**	**Ra-228**
Norway-2	0.00	0.00	0.00
Norway-3	0.00	0.00	0.00
Norway-4	0.01	0.00	0.00
Norway-5	0.02	0.06	0.02
Norway-6	0.00	0.00	0.00
Norway-7	0.00	0.00	0.00

5.3 Conclusions

The dilution of produced water at 500 m distance from the discharge location at seven installations in the Norwegian sector and 16 in the UK sector has been modelled using the DREAM model. The installations used in this study represent a wide range of installation types when it comes to both location and the size of the discharge. It is considered that the minimum dilution results are precautionary. Although there are some situations in which the conservative estimates of the additional activity concentrations at 500 m exceed the environmental assessment criterion, the estimated additional concentrations are generally lower than this value.

6 Summary

The additional concentrations of naturally occurring radionuclides in seawater resulting from discharges of produced water from oil and gas installations in the OSPAR maritime area were evaluated using a compartmental numerical modelling approach. These values were compared with indicative background values to evaluate whether total concentrations, including this component, could be considered to be near background values (the first objective of the OSPAR RSS under the NEAES 2010 – 2020). In all cases, modelled additional concentrations were far less than the variations in background levels and far lower than typical low-end background levels. These values were also less than the uncertainties in measurements of background. In practice, this means that any additional concentrations would likely be indistinguishable from background levels measured by routine analytical techniques for environmental monitoring purposes.

The radiological impact of the modelled additional concentrations was also evaluated, using reference environmental concentrations, established by OSPAR RSC for this purpose. In all cases the annual doses from the additional concentrations of these indicator radionuclides in seawater would be below the trivial annual dose of 10 μSv and a small fraction of the concentrations at which effects on biota have been observed. These levels would not result in any radiological impact to humans or the marine environment.

The comparisons with background levels, taken together with assessment on radiological impact, indicate that it is reasonable to consider, for seawater, that the ultimate aim of 'total environmental concentrations of naturally radionuclides are near background levels' is likely to have been achieved.

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OSPAR Agreement 2016-07 (2022 Update) methodology for deriving Environmental Assessment Criteria (EAC)

Appendix A – Bed Sediment Activity Concentrations

The DORIS model estimated surface seabed sediment activity concentrations for all discharged radionuclides and radioactive progeny in all compartments. However, for the purposes of this report only data for Po- 210, Pb-210, Ra-226 and Ra-228 are presented. The activity concentrations in the source compartments are included in Table A1 and those of recipient compartments in Table A2 which show that they span several orders of magnitude ranging from 10^{-11} to 10^{-1} Bq/kg. This compares with activity concentrations in seawater spanning 10^{-15} to 10^{-5} Bq/l. The DORIS compartment numbers in these two tables are shown in Figure 1 in the main section of the report.

Table A1: Surface seabed sediment activity concentrations (Bq/kg) in all DORIS marine source compartments after 10-years of discharges that took place in 2006 – 2015

Source Compartment		**Po-210**	**Pb-210**	**Ra-226**	**Ra-228**
4	Atlantic North N.E. (deep 2000-4000m)	4.19E-07	4.90E-07	2.11E-07	6.92E-08
10	Norwegian Sea	1.82E-02	1.87E-02	3.45E-03	1.28E-03
12	Scottish Waters East	7.73E-04	7.73E-04	1.39E-03	6.66E-04
14	North Sea North	9.70E-03	9.84E-03	1.59E-02	6.85E-03
19	Irish Sea South	4.23E-03	4.48E-03	2.12E-02	3.73E-03
21	Celtic Sea	1.27E-05	1.33E-05	6.53E-05	1.27E-05
38	North Sea South West	4.89E-03	5.12E-03	2.50E-02	1.03E-02
39	North Sea South East	5.73E-03	6.11E-03	3.42E-02	2.40E-02
40	North Sea Central	5.57E-03	5.83E-03	2.84E-02	8.21E-03

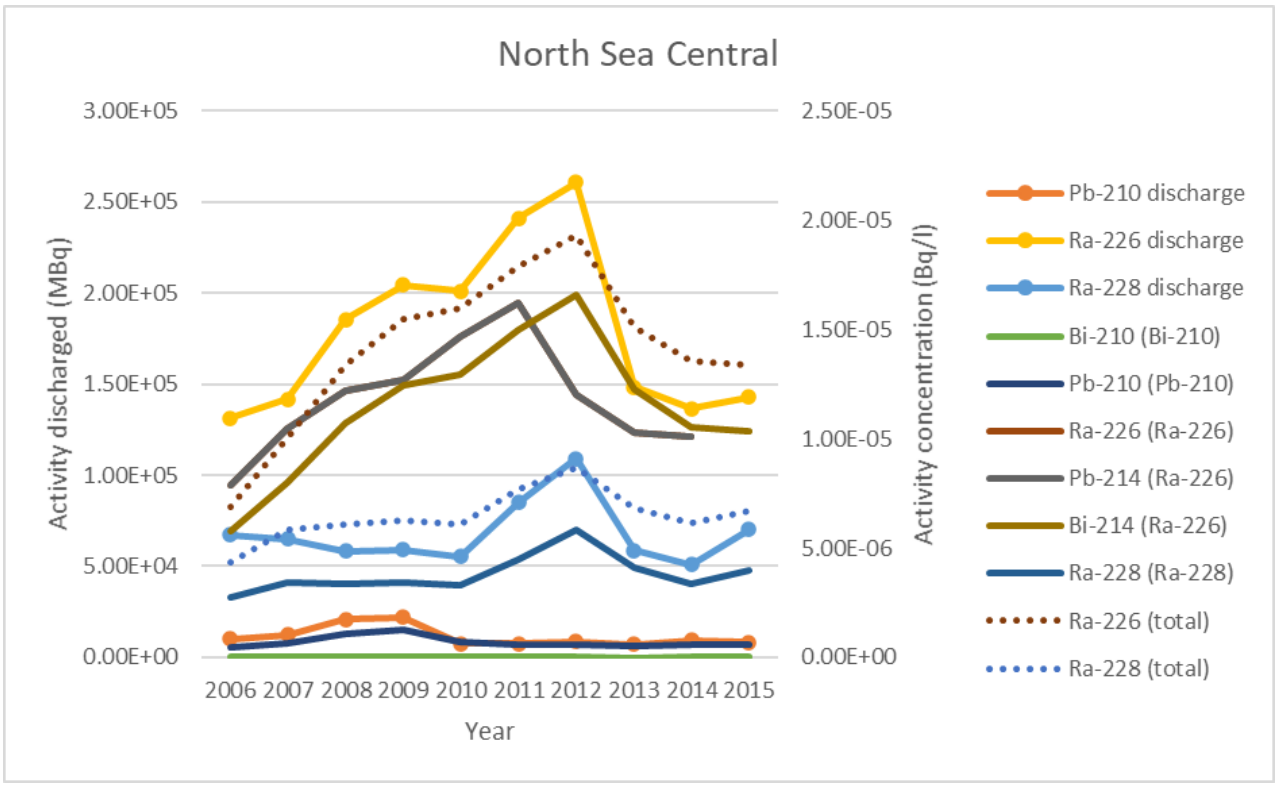
Table A2: Surface seabed sediment activity concentrations (Bq/kg) in all DORIS marine recipient compartments after 10-years of discharges that took place in 2006 – 2015

Recipient Compartment		**Po-210**	**Pb-210**	**Ra-226**	**Ra-228**
1	Other oceans	7.12E-10	8.46E-10	1.98E-10	6.44E-11
5	Other Atlantic	3.97E-07	4.34E-07	7.97E-08	2.63E-08
6	Arctic Ocean	4.84E-05	5.16E-05	9.78E-06	3.23E-06
7	Arctic South	6.12E-05	6.68E-05	2.00E-05	6.90E-06
8	Spitzbergen	3.75E-05	4.12E-05	1.69E-05	5.73E-06
9	Kara and Barents Sea	1.46E-04	1.55E-04	1.13E-03	4.00E-04
11	Scottish Waters W.	2.19E-04	2.22E-04	8.46E-04	1.64E-04
13	Irish Sea N.W.	2.65E-03	2.75E-03	1.20E-02	2.02E-03
15	Irish Sea N.E.	2.37E-03	2.47E-03	1.06E-02	1.79E-03
16	Irish Sea W.	3.98E-03	4.17E-03	1.95E-02	3.25E-03
17	Irish Sea S.E.	3.02E-03	3.16E-03	1.41E-02	2.38E-03
18	Cumbrian Waters	4.04E-03	4.24E-03	2.16E-02	3.29E-03
20	Liverpool and Morecambe Bays	3.25E-03	3.43E-03	1.71E-02	2.65E-03
22	Bristol Channel	1.14E-05	1.19E-05	5.55E-05	1.06E-05
23	Bay of Biscay	3.64E-04	3.63E-04	1.26E-05	2.63E-06
24	French Continental Shelf	1.56E-04	1.55E-04	2.29E-05	4.71E-06
25	Cantabrian Sea	6.88E-05	6.86E-05	1.65E-05	3.48E-06

Recipient Compartment		Po-210	Pb-210	Ra-226	Ra-228
26	Portuguese Continental Shelf	4.11E-05	4.07E-05	3.55E-06	9.89E-07
27	Gulf of Cadiz	9.25E-05	9.18E-05	2.04E-06	5.99E-07
28	Mediterranean	7.79E-07	7.74E-07	7.56E-08	2.64E-08
29	English Channel W.	3.31E-05	3.48E-05	1.77E-04	8.87E-05
30	Channel Islands	8.84E-05	9.35E-05	4.87E-04	2.99E-04
31	Cap de la Hague	1.27E-04	1.34E-04	7.12E-04	4.53E-04
32	Lyme Bay	1.16E-04	1.23E-04	6.48E-04	4.10E-04
33	Baie de la Seine	4.95E-04	5.25E-04	2.83E-03	1.90E-03
34	Sam's Beach	6.14E-04	6.53E-04	3.55E-03	2.42E-03
35	Central Channel S.E.	5.07E-04	5.39E-04	2.92E-03	1.98E-03
36	Central Channel N.E.	5.48E-04	5.82E-04	3.16E-03	2.14E-03
37	Isle of Wight	5.50E-04	5.84E-04	3.17E-03	2.15E-03
41	North Sea E.	5.23E-03	5.54E-03	2.91E-02	1.65E-02
42	Irish Sea N.	2.72E-03	2.82E-03	1.23E-02	2.08E-03
43	Skagerrak	8.96E-02	9.16E-02	1.48E-01	7.05E-02
44	Kattegat (surface 0-20m)	N/A	N/A	N/A	N/A
45	Kattegat (bottom 20-120m)	2.31E-03	2.56E-03	1.91E-02	8.88E-03
46	Belt Sea (surface 0-14m)	N/A	N/A	N/A	N/A
47	Belt Sea (bottom 14-44m)	1.48E-03	1.64E-03	1.19E-02	5.45E-03
48	Bothnian Bay	5.00E-06	4.89E-06	2.39E-05	8.50E-06
49	Bothnian Sea	3.60E-05	3.55E-05	1.83E-04	6.74E-05
50	Baltic Sea E. (bottom 53-163m)	4.57E-04	4.77E-04	2.88E-03	1.17E-03
51	Baltic Sea E. (surface 0-53m)	N/A	N/A	N/A	N/A
52	Baltic Sea W. (bottom 49-159m)	3.06E-04	3.11E-04	1.73E-03	6.63E-04
53	Baltic Sea W. (surface 0-49m)	N/A	N/A	N/A	N/A
54	Gulf of Finland	9.06E-05	9.10E-05	4.85E-04	1.82E-04
55	Gulf of Riga	9.38E-05	9.54E-05	5.13E-04	1.93E-04

The seawater and surface seabed sediment activity concentrations over the 10-year period can be seen in Figures A1 and A2 for the North Sea Central source compartment and the Portuguese Continental Shelf recipient compartment. In North Sea Central, within the 10-year period it was previously concluded that the seawater activity concentrations were in an effective steady state due to the variation in discharges. In contrast, within the 10-year period the surface seabed sediment activity concentrations continually increase despite the variation in discharges. In the Portuguese Continental Shelf, the activity concentrations for both seawater and seabed sediment are several orders of magnitude lower than the North Sea Central source compartment, but the dominant radionuclides are different. The activity concentrations in seawater are dominated by Ra-226 and Ra-228 whereas seabed sediments are dominated by Po-210 and Pb-210.

From the activity distribution maps, Figures A3 and A4, it can be seen that the highest seawater activity concentration tends to be found in the North Sea Central source compartment, in which a significant portion of the discharges took place. In contrast, the highest seabed sediment activity concentration tends to be found in compartments adjacent to North Sea Central, in which a lower portion of the discharges took place or no discharges took place at all.



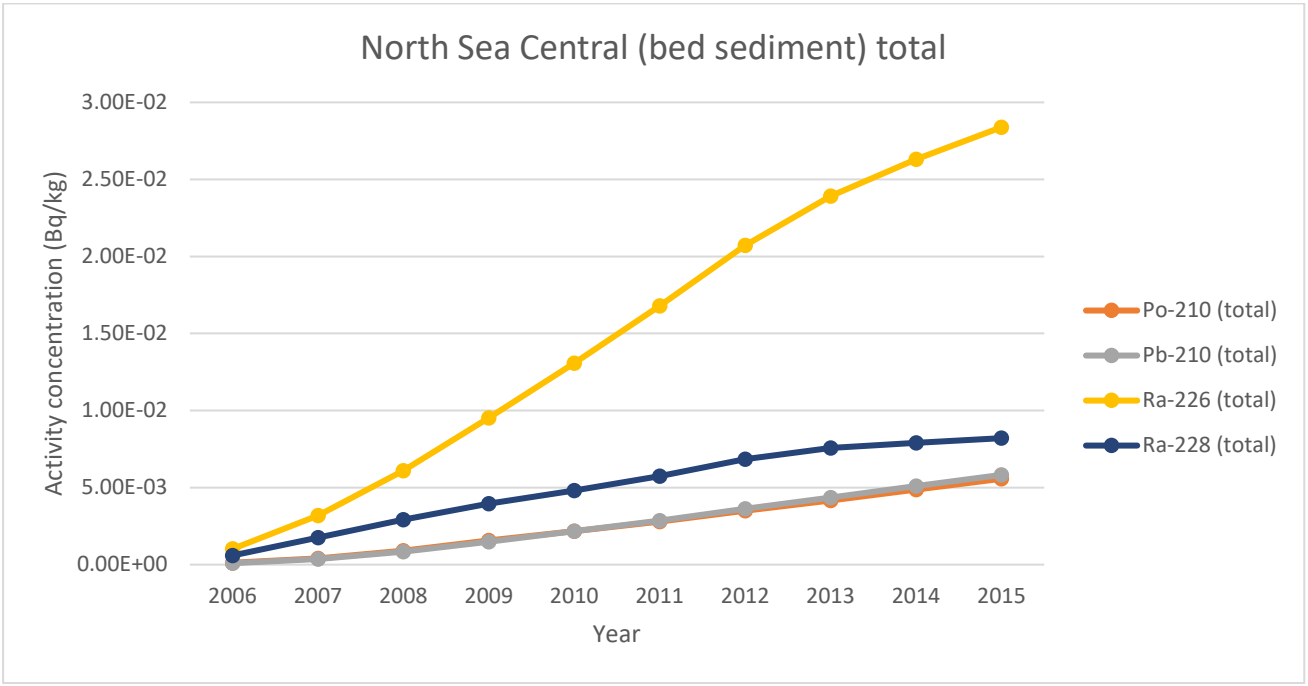
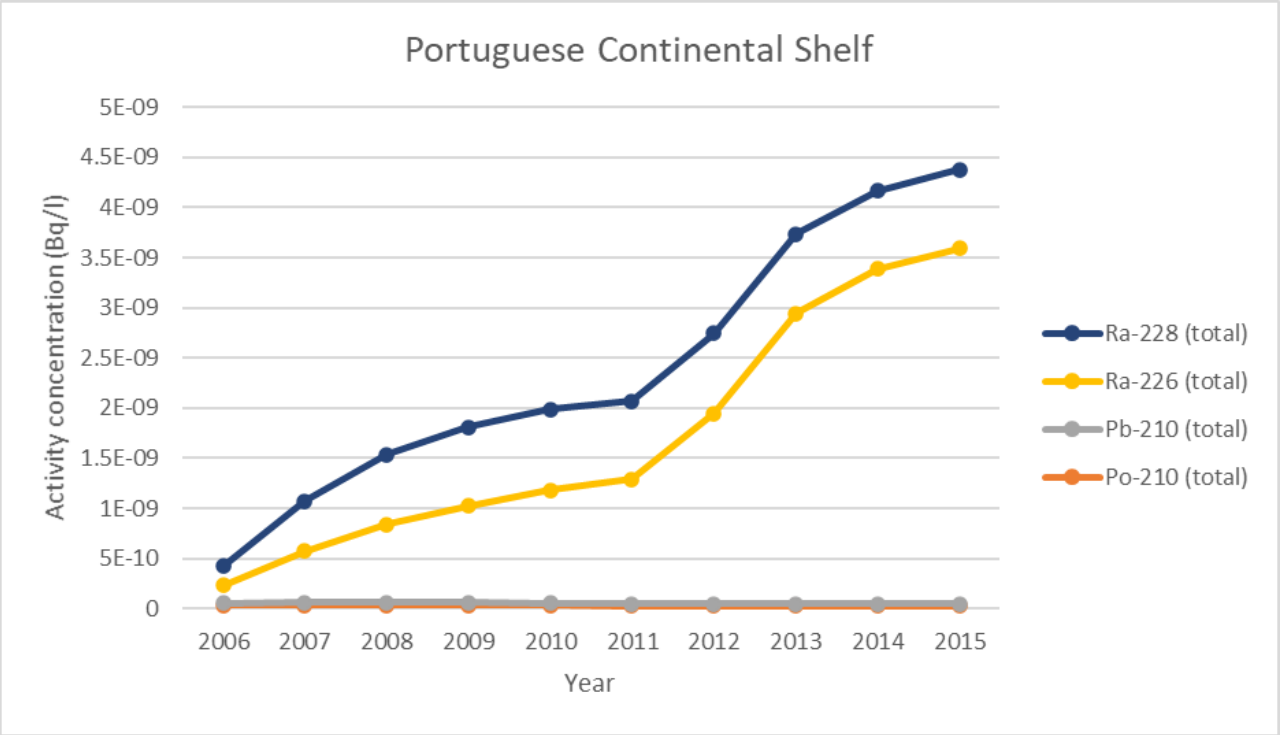


Figure A1: Filtered seawater activity concentrations (Bq/l) from discharges into the North Sea Central compartment and from total discharges, and surface seabed sediment activity concentrations (Bq/kg) in the North Sea Central from (total) discharges to all source compartments in the period 2006 – 2015.



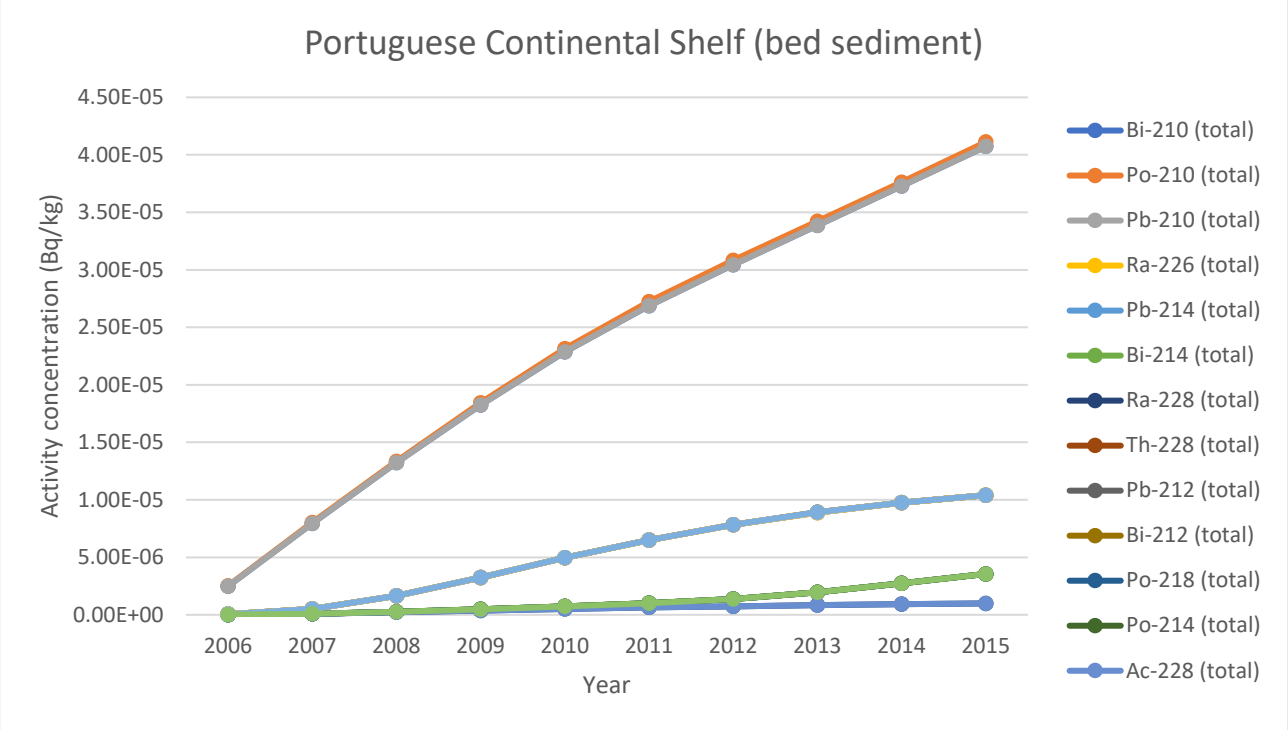


Figure A2: Filtered seawater activity concentrations (Bq/l) and surface seabed sediment activity concentrations (Bq/kg) in the Portuguese Continental Shelf recipient compartment during 10 years of discharges that took place in 2006 – 2015.

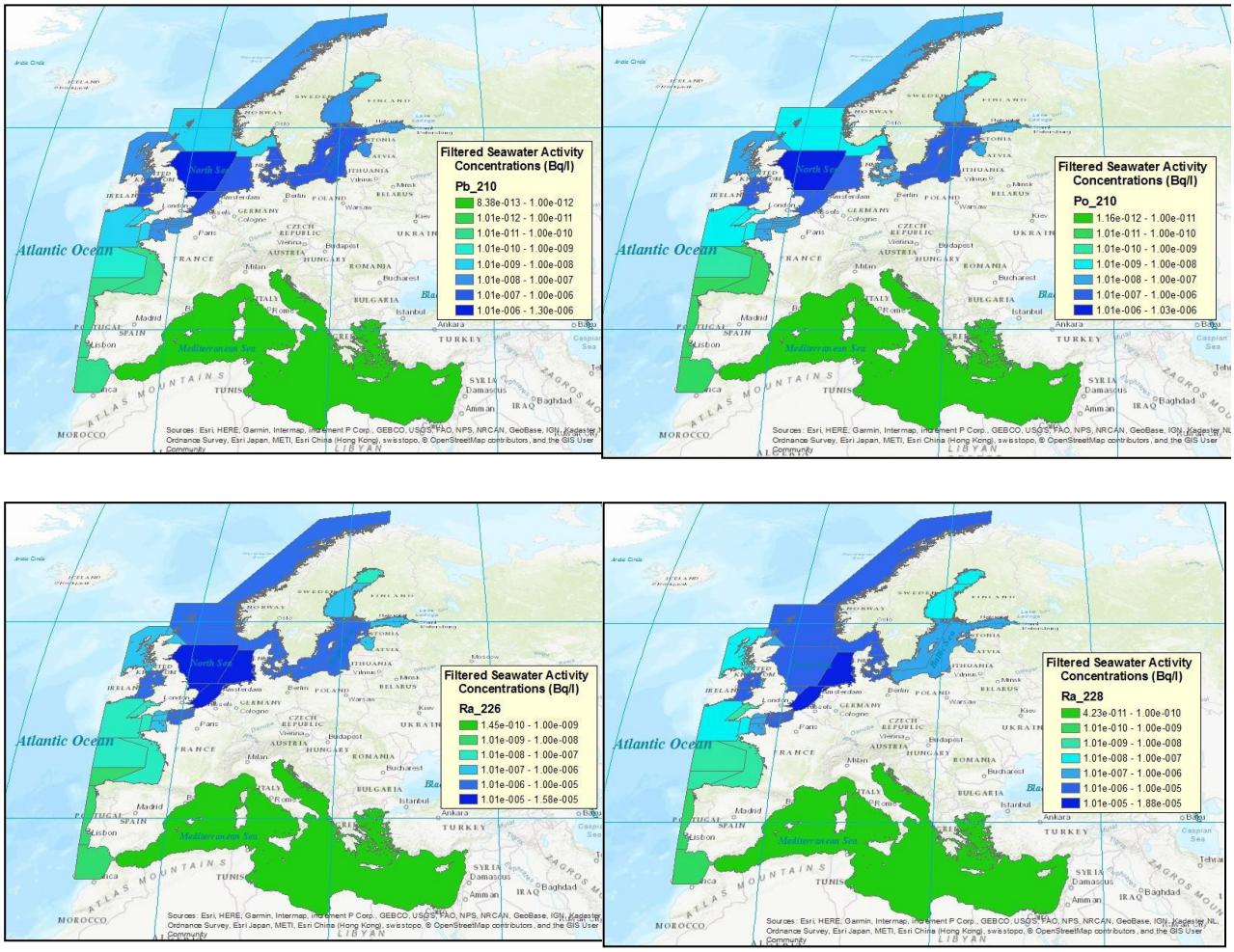


Figure A3: Filtered seawater activity concentrations (Bq/l) in the European compartments of the DORIS model after 10 years of discharges that took place in 2006 – 2015

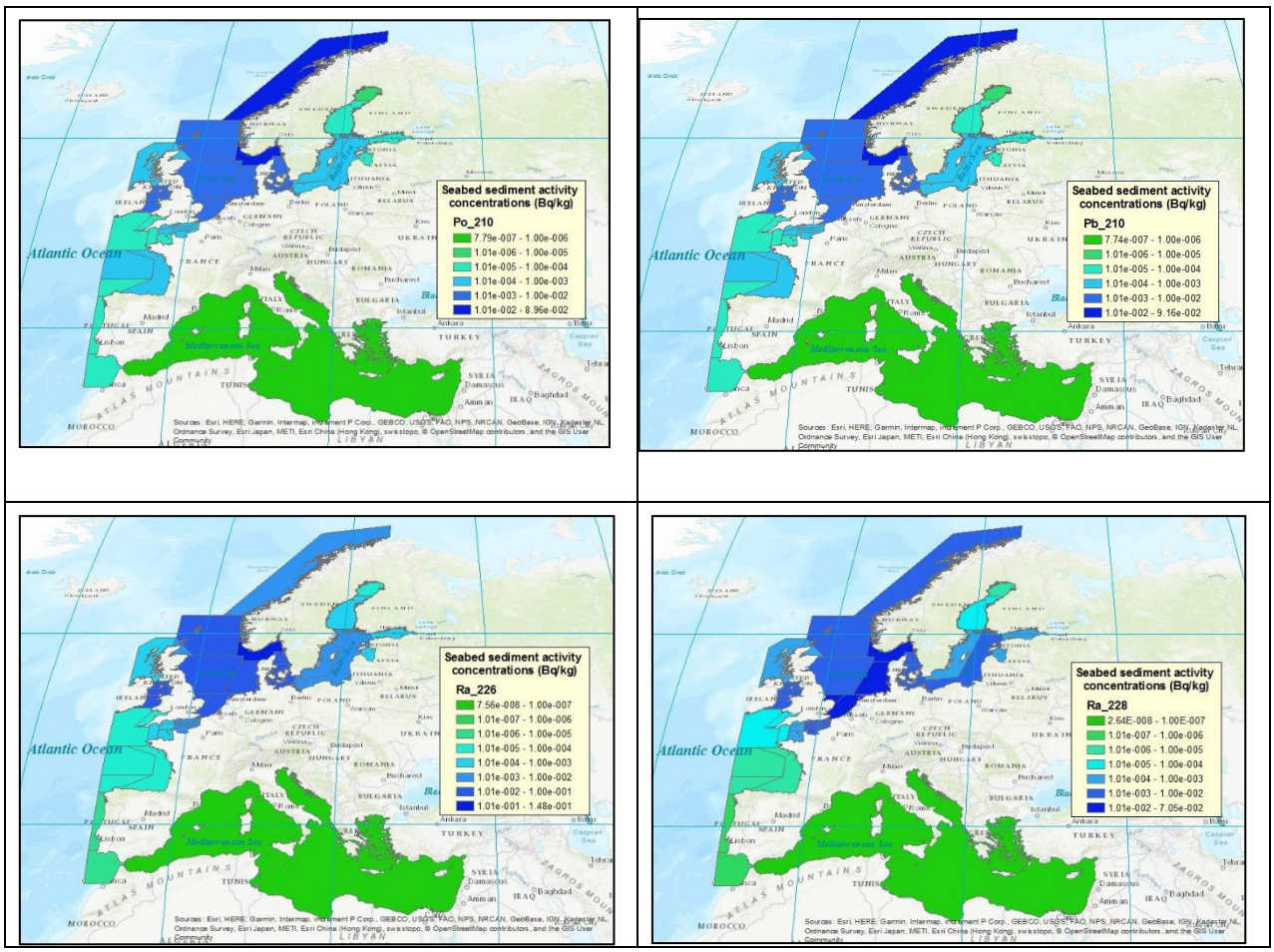


Figure A4: Surface seabed sediment activity concentrations (Bq/kg) in the European compartments of the DORIS model after 10 years of discharges that took place in 2006 – 2015.

Appendix B – Estimated concentrations as a percentage of the EAC

The table below provides a screening level radiological assessment of discharges from facilities considered in this work. Cells in the table are colour coded according to:

	conc < EAC/100
	EAC/100 < conc < EAC/10
	EAC/10 < conc < EAC/2
	EAC/2 < conc <EAC
	conc >EAC

DORIS Source Compartment	Country	Name	Concn at 500 m as a percentage of EAC		
			Pb-210	Ra-226	Ra-228
North Sea Central	Denmark	DAN FC	0.0	1.2	0.1
North Sea Central	Denmark	DAN FF	0.0	4.3	1.3
North Sea Central	Denmark	GORM C	0.0	0.9	0.2
North Sea Central	Denmark	GORM F	0.0	0.5	0.0
North Sea Central	Denmark	HARALD A	0.0	3.3	0.7
North Sea Central	Denmark	TYRA EF	0.0	6.7	1.3
North Sea Central	Denmark	TYRA WA	0.0	2.1	0.9
North Sea Central	Denmark	TYRA EA	0.0	3.2	0.5
North Sea Central	Denmark	HALFDAN DA	0.0	4.5	0.7
North Sea Central	Denmark	SIRI	0.0	0.9	0.3
North Sea Central	Denmark	SYD ARNE	40.7	6.5	1.1
North Sea Central	Denmark	DAN FG	0.0	6.1	1.1
North Sea Central	Denmark	HALFDAN BD	0.0	2.4	0.9
North Sea Central	Germany	A6-A	0.0	0.4	0.0
Celtic Sea	Ireland	KINSALE HEAD ALPHA	0.2	0.0	0.0
North Sea South East	Netherlands	HELDER	34.4	17.2	6.0
North Sea South East	Netherlands	HELM	17.2	11.3	4.4
North Sea South East	Netherlands	HOORN	25.9	15.6	4.9
North Sea Central	Netherlands	F2-A-HANZE	17.2	7.6	1.1
North Sea Central	Netherlands	F16-A	95.8	1.0	0.2
North Sea South East	Netherlands	P11-B-DE RUYTER	62.0	92.7	23.8
North Sea South East	Netherlands	P9-HORIZON A	87.0	114.0	86.7
North Sea North	United Kingdom	ALBA FSU	0.1	0.0	0.0
Irish Sea South	United Kingdom	DOUGLAS FPSO	3.9	14.6	3.9
North Sea North	United Kingdom	CHESTNUT HUMMINGBIRD FPSO	2.8	2.3	0.7
North Sea North	United Kingdom	ETTRICK FPSO AOKA MIZU	0.9	5.7	0.7
North Sea North	United Kingdom	DONAN FPSO GLOBAL PRODUCER III	299.9	7.5	2.8
North Sea North	United Kingdom	WEST DON NORTHERN PRODUCER	4.0	2.3	0.8
North Sea North	United Kingdom	ATHENA FPSO	10.9	0.1	0.0
North Sea Central	United Kingdom	WINGATE PLATFORM	65.0	1.4	0.4

North Sea North	United Kingdom	HUNTINGTON FPSO	0.3	2.6	0.6
North Sea Central	United Kingdom	BABBAGE PLATFORM	0.9	0.0	0.0
North Sea North	United Kingdom	GOLDEN EAGLE PUQ PLATFORM	0.1	0.0	0.0
Atlantic Ocean North East	United Kingdom	FOINAVEN FPSO PETROJARL	3.7	0.5	0.4
North Sea North	United Kingdom	GRYPHON A	670.3	29.5	3.3
North Sea North	United Kingdom	BALMORAL FPV	8.4	20.7	7.3
North Sea North	United Kingdom	MACCULLOCH FPSO	1.8	7.3	2.7
North Sea Central	United Kingdom	GUILLEMOT, TEAL FPSO ANASURIA	11.7	4.2	1.6
North Sea Central	United Kingdom	ANGUS FPSO	23.4	43.1	8.6
Scottish Waters East	United Kingdom	BEATRICE AP	0.9	0.2	0.3
North Sea Central	United Kingdom	CLEETON CPQ	0.0	0.0	0.0
Irish Sea South	United Kingdom	DOUGLAS DA	1.6	13.4	3.6
North Sea South West	United Kingdom	EXCALIBUR A	0.0	0.0	0.0
North Sea Central	United Kingdom	GALAHAD	9.4	1.9	0.6
North Sea South West	United Kingdom	GUINEVERE	0.1	0.0	0.0
North Sea South West	United Kingdom	HEWETT; 48/29 A	0.0	0.0	0.0
North Sea Central	United Kingdom	HYDE	2.4	0.7	0.2
North Sea South West	United Kingdom	INDE [WEST] AC	0.2	0.0	0.0
North Sea South West	United Kingdom	LANCELOT	0.0	0.0	0.0
North Sea South West	United Kingdom	LEMAN AD1	0.6	0.2	0.1
North Sea North	United Kingdom	BUCHAN A	3.1	11.3	5.1
North Sea Central	United Kingdom	ROUGH AD	0.0	0.0	0.0
North Sea Central	United Kingdom	WEST SOLE WA	0.4	0.1	0.0
North Sea North	United Kingdom	ALBA NORTHERN	18.7	5.4	2.9
North Sea North	United Kingdom	ALWYN NORTH NAB	0.2	0.0	0.0
North Sea North	United Kingdom	ANDREW	3.4	18.0	3.6
North Sea North	United Kingdom	ARMADA PLATFORM	1.2	5.5	0.8
North Sea Central	United Kingdom	AUK A	2.1	15.3	1.4
North Sea North	United Kingdom	BERYL B	4.6	2.2	0.7
North Sea North	United Kingdom	BRAE A	6.8	25.0	4.1
North Sea North	United Kingdom	BRAE B	2.3	0.2	0.1
North Sea North	United Kingdom	BRAE EEAST	0.1	0.2	0.0
North Sea North	United Kingdom	BRITTANIA PLATFORM	7.6	15.9	4.6
North Sea North	United Kingdom	BRUCE PUQ	0.1	0.2	0.1
North Sea North	United Kingdom	CLAYMORE A	68.4	30.0	12.5
North Sea Central	United Kingdom	CLYDE	1.9	36.1	3.1
North Sea North	United Kingdom	CORMORANT NNORTH	10.6	2.6	2.1
North Sea North	United Kingdom	EIDER	7.1	3.1	2.5
North Sea North	United Kingdom	NORTH EVEREST NORTH	0.1	0.0	0.0
North Sea North	United Kingdom	FORTIES FA	52.1	35.4	9.2
North Sea North	United Kingdom	FORTIES FB	12.6	7.9	2.5
North Sea North	United Kingdom	FORTIES FC	19.1	22.6	7.6
North Sea North	United Kingdom	FORTIES FD	10.1	21.7	6.7
North Sea Central	United Kingdom	FULMAR A	12.7	27.5	7.9
North Sea Central	United Kingdom	GANNET A	4.3	8.9	2.6
North Sea North	United Kingdom	HARDING PLATFORM	0.1	0.2	0.0

North Sea North	United Kingdom	HEATHER A PLATFORM	4.3	1.6	1.4
North Sea Central	United Kingdom	JUDY RISER PLATFORM	8.5	2.2	0.5
North Sea Central	United Kingdom	KITTIWAKE A	3.3	13.5	0.9
North Sea Central	United Kingdom	LOMOND	0.9	2.5	0.3
North Sea North	United Kingdom	MAGNUS	8.6	0.9	1.3
North Sea Central	United Kingdom	MONTROSE A	4.4	11.0	1.1
Irish Sea South	United Kingdom	MORECAMBE CPP1	0.0	0.0	0.0
North Sea North	United Kingdom	NELSON	13.3	60.8	15.2
North Sea North	United Kingdom	NINIAN NORTH	0.0	1.5	3.1
North Sea North	United Kingdom	NINIAN SOUTH	25.4	2.2	3.9
North Sea North	United Kingdom	PIPER B	11.4	19.6	3.5
North Sea Central	United Kingdom	ROUGH BD	0.0	0.0	0.0
North Sea North	United Kingdom	SCOTT JD	11.8	56.6	4.8
North Sea North	United Kingdom	TARTAN A	0.7	6.3	1.3
North Sea North	United Kingdom	TERN	7.6	7.3	3.8
North Sea North	United Kingdom	THISTLE A	14.8	5.5	4.8
North Sea North	United Kingdom	TIFFANY	2.3	1.7	0.5
North Sea North	United Kingdom	BERYL A	10.1	0.5	0.3
North Sea North	United Kingdom	BRENT BRAVO	10.6	0.6	0.5
North Sea North	United Kingdom	BRENT CHARLIE	67.1	1.6	1.8
North Sea North	United Kingdom	BRENT DELTA	2.4	0.1	0.1
North Sea North	United Kingdom	CORMORANT SSOUTH A	11.5	1.3	1.8
North Sea North	United Kingdom	DUNLIN A	5.2	1.2	1.1
North Sea North	United Kingdom	NINIAN CENTRAL	0.0	6.8	5.6
North Sea Central	United Kingdom	RAVENSPURN NORTH [NTH]:CPP	9.6	1.3	0.3
North Sea Central	United Kingdom	JANICE A	83.5	4.5	3.2
North Sea Central	United Kingdom	CURLEW FPSO	0.0	0.0	0.0
North Sea Central	United Kingdom	MALORY PLATFORM	0.0	0.0	0.0
North Sea North	United Kingdom	ROSS FPSO BLEO HOLM	4.3	12.0	3.6
North Sea Central	United Kingdom	TRENT PLATFORM	0.0	0.0	0.0
North Sea Central	United Kingdom	TYNE PLATFORM	0.2	0.0	0.0
North Sea Central	United Kingdom	PIERCE FPSO HAEWENE BRIM	0.6	2.3	0.4
North Sea Central	United Kingdom	SHEARWATER C PUQ PLATFORM	0.7	1.7	0.3
North Sea South West	United Kingdom	WAVENEY PLATFORM	0.0	0.0	0.0
North Sea Central	United Kingdom	BANFF FPSO	0.7	1.0	0.3
North Sea Central	United Kingdom	ELGIN PUQ PLATFORM	0.6	0.1	0.0
North Sea Central	United Kingdom	GUILLEMOT WEST FPSO	5.6	51.0	10.1
North Sea Central	United Kingdom	BANFF FSU APOLLO SPIRIT	0.0	0.1	0.0
North Sea North	United Kingdom	CLAIR PHASE 1 PLATFORM	0.5	0.2	0.1
Irish Sea South	United Kingdom	MILLOM WEST PLATFORM	0.1	0.1	0.0

North Sea North	United Kingdom	BUZZARD PRODUCTION PLATFORM	0.6	2.2	0.2
North Sea North	Norway	OSEBERG A	0.3	0.9	0.3
North Sea North	Norway	STATFJORD A	33.7	3.6	2.1
North Sea North	Norway	STATFJORD B	56.8	4.8	1.9
North Sea North	Norway	STATFJORD C	74.8	15.6	7.3
North Sea Central	Norway	TOR	13.6	5.0	0.3
North Sea Central	Norway	ELDFISK B	9.4	13.6	0.6
North Sea North	Norway	GULLFAKS A	25.4	19.6	8.2
North Sea North	Norway	GULLFAKS B	54.8	18.5	8.5
North Sea Central	Norway	ULA PP	77.0	70.1	12.4
North Sea North	Norway	SNORRE A	56.1	24.0	9.8
North Sea North	Norway	OSEBERG C	0.2	0.6	0.2
North Sea Central	Norway	GYDA	28.1	8.1	1.2
North Sea North	Norway	SLEIPNER A	1.5	0.3	0.1
Norwegian Sea	Norway	DRAUGEN	102.7	41.1	9.9
Norwegian Sea	Norway	HEIDRUN	1.6	4.1	1.9
North Sea North	Norway	GULLFAKS C	44.7	32.6	10.9
North Sea North	Norway	VESLEFRIKK B	26.7	4.2	3.8
North Sea North	Norway	BRAGE	35.7	88.5	35.0
North Sea North	Norway	SLEIPNER T	0.1	0.1	0.0
North Sea North	Norway	VISUND	6.0	7.3	2.6
Norwegian Sea	Norway	NJORD A	4.0	13.5	9.7
North Sea Central	Norway	EKOFISK J	134.0	13.9	3.1
North Sea North	Norway	TROLL B	65.7	193.8	67.6
North Sea North	Norway	TROLL A	0.3	0.0	0.0
North Sea North	Norway	JOTUN A	46.6	28.2	11.1
North Sea North	Norway	TROLL C	54.5	183.1	58.7
Norwegian Sea	Norway	NORNE floating steel	52.2	20.1	13.6
Norwegian Sea	Norway	ÅSGARD A	5.9	16.2	6.7
North Sea North	Norway	BALDER FPU	44.5	23.9	5.5
North Sea North	Norway	PETROJARL VARG	27.7	5.6	1.0
Norwegian Sea	Norway	ÅSGARD B	3.8	5.9	1.4
North Sea North	Norway	OSEBERG SØR	0.6	1.1	0.4
North Sea North	Norway	SNORRE B	30.0	56.1	20.9
North Sea North	Norway	GRANE	10.0	9.9	3.9
North Sea Central	Norway	EKOFISK M	75.8	8.8	2.6
Norwegian Sea	Norway	KRISTIN	13.8	37.1	11.7
North Sea North	Norway	ALVHEIM floating steel	46.5	52.9	20.1
North Sea Central	Norway	VALHALL PH	14.9	2.9	0.9
North Sea North	Norway	GJØA	8.4	7.4	3.9
Norwegian Sea	Norway	SKARV FPSO	2.8	1.2	0.2

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Our vision is a clean, healthy and biologically diverse North-East Atlantic Ocean, which is productive, used sustainably and resilient to climate change and ocean acidification

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